Technical Publication 011-06
Prepared in Cooperation with the United States Geological Survey

Evaluation of the Downward Migration of Saltwater to the Upper Floridan Aquifer in the Savannah, Georgia, and Hilton Head Island, South Carolina, Area

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South Carolina Department of Health and Environmental Control

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Front cover image: The Jericho Well Field, located on Port Royal Island approximately one mile northwest of Parris Island, South Carolina, provided fresh groundwater to the military base at Parris Island from the late 1920s to the early 1940s. Pumpage from the wellfield eventually ceased as chloride concentrations increased. This image of an abandoned pump house in the Jericho Well Field is a reminder of the sensitive environmental conditions that impede groundwater development in coastal areas. Photography: Camille Ransom, III, 2000.

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Abstract

The Upper Floridan aquifer underlies all of Florida, most of the Georgia and Alabama Coastal Plain, and large parts of coastal South Carolina. The aquifer is composed primarily of carbonate rock of varying permeability that ranges in age from middle Eocene to early Miocene. Where present in Georgia, South Carolina, and Florida, the aquifer is the primary source of groundwater supply for domestic, municipal, and industrial use. In the study area, the Upper Floridan aquifer is confined above by the upper confining unit of Miocene age that, in turn, is overlain by more recent undifferentiated surficial sediments. Collectively, the carbonates that compose the Upper Floridan aquifer and the overlying sediments are thickest in the southwestern part of coastal Georgia and thin toward the northeast near South Carolina.

Prior to groundwater development, potentiometric heads in the Upper Floridan aquifer ranged between 5 and 35 feet above mean sea level throughout most of the study area until about 1888 when groundwater withdrawals began in the vicinity of Savannah, Georgia. By 1943, withdrawals had reached approximately 42 million gallons per day and continued to increase until 1990 when withdrawals peaked at 88 million gallons per day in Savannah and 14 million gallons per day on nearby Hilton Head Island, South Carolina. After 1990, withdrawals declined and by 1998 withdrawals were approximately 80 million gallons per day. The cone of depression created by the 1998 pumpage lowered the potentiometric surface below mean sea level over an area greater than 2,300 square miles, of which about 1,200 square miles (53 percent) are overlain by saltwater marshes, rivers, and the Atlantic Ocean.

The upper confining unit is characterized by very fine silty to clayey sand that can impede but not prevent vertical flow between overlying sources of water and the underlying freshwater in the Upper Floridan aquifer. The direction of vertical flow through the upper confining unit is dependent on the potentiometric heads in the Upper Floridan aquifer, and heads have been influenced by glacial episodes that control the rise and fall of sea level. Prior to groundwater development, the most recent process of upward freshwater discharge from the Upper Floridan aquifer probably started at the end of the last glacial episode over 100,000 years ago and continued until about 1943. The upward freshwater discharge that occurred over 100,000 years acted to displace saltwater present in the upper confining unit as a result of marine deposition or changes in sea level. After about 1943, groundwater withdrawals lowered the potentiometric surface below mean sea level, as defined by the North American Vertical Datum of 1988 (NAVD 88) for a distance of approximately 12 miles from Savannah, Georgia, the natural upward discharge of freshwater was reversed and, where present, saltwater began to migrate downward through the upper confining unit to the Upper Floridan aquifer. Although the potential for saltwater to migrate downward through the upper confining unit to the Upper Floridan aquifer had been suggested by other investigators, no data had been collected to test this hypothesis until this investigation.

To test this hypothesis, onshore and offshore locations were selected to collect data necessary to demonstrate downward migration of saltwater through the upper confining unit. At each site, core samples from the upper confining unit were collected and pore water was extracted and analyzed for dissolved chloride concentration. Pore-water analyses indicated a trend of high chloride concentrations near the top of the upper confining unit that decreased with depth at both the offshore and onshore locations. The results of the pore-water analyses indicated the downward migration of surficial saltwater through the upper confining unit overlying the Upper Floridan aquifer. These data also indicated the occurrence of an alternative pathway for saltwater to enter coastal aquifers by a vertical pathway through confining units in addition to the known pathways of lateral encroachment and direct entry through breaches in the upper confining unit.

Darcy's Law was used to estimate the volume of downward flow of saltwater through the upper confining unit. Darcy's Law does not account for differences in the rate of movement that result from dispersion and diffusion of a solute such as chloride, which is denser than freshwater. After accounting for the effect of saltwater density on freshwater hydraulic gradients, the effect of saltwater on the hydraulic gradient was found to be insignificant because the primary driving force is the magnitude of the hydraulic gradient. This approach indicated that an area of approximately 382 square miles east and northeast of Savannah, Georgia, may be contributing 7.7 million gallons per day of downward flow to the Upper Floridan aquifer. Because this area may affect water quality in the Upper Floridan aquifer in the future, it is considered to be an area of concern.

To further evaluate the area of concern, a one-dimensional solute-transport equation was used to simulate the future arrival times for a given concentration of

chloride to reach the top of the Upper Floridan aquifer through the upper confining unit. These simulations predicted that the arrival times for saltwater having a chloride concentration of 500 milligrams per liter ranged from as early as 25 years ago to 113 years from 2005, with an average arrival time of approximately 36 years from 2005 within the area of concern.

Introduction

The Upper Floridan aquifer has served as the primary source of water supply in the Savannah, Georgia (Ga.), Hilton Head Island, South Carolina (S.C.), area, since the late 19th century. The first public supply wells were constructed in 1887 for municipal supply at Savannah, and municipal and industrial pumping steadily increased during the next 100 years. Development of Hilton Head Island as a vacation and retirement community began in the 1960's and wells open to the Upper Floridan aquifer provided water for municipal supply and for golf course and domestic irrigation. By the early 1990's, the combined demand for groundwater at Savannah and Hilton Head Island had exceeded 100 million gallons per day (Mgal/d). This demand for groundwater amid concerns of saltwater encroachment caused the States of Georgia and South Carolina to pass legislation in 1972 and 1982, respectively, to create "Capacity Use Areas" for the purpose of managing groundwater withdrawals by requiring permits for large users.

The Capacity Use Program in South Carolina decreased permitted water use from the Upper Floridan aquifer on Hilton Head Island from a peak of 14.8 Mgal/d to 9.7 Mgal/d. Decreasing the permitted water use promoted conservation and encouraged the development of new sources. For example, golf courses were required to use reclaimed water as it became available and to develop wells in the Middle Floridan aquifer (Gawne and Park, 1992). In some cases, golf courses blended water from the Middle Floridan aquifer with water from shallow lagoons designed to capture runoff. In 1992, South Island Utilities, located in the southern part of Hilton Head Island, constructed a 3,800-foot (ft) well in the Middendorf aquifer that required reverse-osmosis technology to treat brackish water to supplement municipal supplies. Utilities in the northern half of the island purchased surface water from the Beaufort-Jasper Water and Sewer Authority (BJWSA) to supplement supplies. With the exception of South Island Utilities, surface water is now used by all major developments in southern Beaufort County, S.C.

The Georgia Environmental Protection Division (GaEPD) responded to concerns of saltwater encroachment by working closely with the Georgia Legislature, U.S. Geological Survey (USGS), S.C. Department of Health and Environmental Control (SCDHEC), permitted stakeholders, and public interest groups to draw attention to the groundwater problems facing the area. The Georgia Coastal Sound Science Initiative was begun in 1997 by the GaEPD to provide data to assist with the management of groundwater withdrawals from the Upper Floridan aquifer in the 24 coastal counties of Georgia and adjoining parts of South Carolina. The investigation reported herein, to evaluate downward saltwater migration through the upper confining unit, was undertaken as part of the SCDHEC contribution to the Georgia Coastal Sound Science Initiative and was performed in cooperation with the USGS.

In April of 1997, GaEPD released the "Interim Strategy for Managing Saltwater Intrusion in the Upper Floridan Aquifer in Southeastern Georgia". The strategy, in conjunction with the Georgia Coastal Sound Science Initiative, provided funds to study the occurrence and use of groundwater in 24 coastal counties in Georgia and adjoining parts of South Carolina and Florida. The Interim Strategy outlined the scope of work and funding for major scientific studies and mandated a 10-Mgal/d reduction of groundwater withdrawals in the Savannah area.

Purpose and Scope

The purpose of this investigation was (1) to determine the occurrence, distribution, volume, and rate of downward migration of saltwater through the upper confining unit into the top of the Upper Floridan aquifer to the north, east, and southeast of Savannah, Ga., and (2) to present results pertinent to Georgia's permanent management strategy for the Upper Floridan aquifer.

This study relied on direct measurements of chloride concentrations from pore water extracted from selected cores at two locations. The first site was one of four offshore locations where pore water was collected as a companion project to an offshore drilling investigation begun in August 1999 by the USGS. Of the four locations, only one site (the 7-mile offshore site; Falls and others, 2005) retrieved core that could be used as part of this investigation. The second site, drilled specifically for this investigation, was located onshore near Bull River between Tybee Island, Ga., and the pumping center at Savannah. Data obtained from drilling, including core collection and pore-water analyses at the Bull River onshore site, ended in April of 2001. Additional data from published reports were used to estimate head differences and thicknesses for the upper confining unit, groundwater withdrawals from the Upper Floridan aquifer, and to estimate a water budget for the Savannah and Hilton Head Island area.

Two methods were used to estimate the water-quality changes resulting from saltwater moving from the surface, through the upper confining unit, and into the top of the Upper Floridan aquifer. The first method used Darcy's Law (Darcy, 1856) to estimate the volume of water moving downward through the thickness of the upper confining unit. The second method used a one-dimensional solute-transport equation to simulate the time for water with a chloride concentration of 500 milligrams per liter (mg/L) to reach the top of the Upper Floridan aquifer assuming no change in 1998 groundwater withdrawals. This report does not address how future water-quality changes in parts of the Upper Floridan aquifer will affect potable water supplies or how potential water-quality changes would respond to changes in pumping.

Previous Investigations

Numerous reports are available that describe the hydrogeology and water use of the Upper Floridan aquifer in the study area (see Landmeyer and Belval, 1996, and references therein). The following discussion summarizes only those investigations that discuss or describe the potential for either freshwater or saltwater to migrate downward through the upper confining unit.

The first investigation to suggest the possible occurrence of downward migration of saltwater through the upper confining unit was conducted by Counts and Donsky (1963). Using Darcy's Law, they used a vertical permeability of 0.001 gallons per day per square foot (gpd/ft^2), an upper confining unit thickness of 150 ft, and a hydraulic-head difference of 200 ft across the upper confining unit, to calculate the volume of water moving downward. The results showed that 37,000 gallons per day (gal/d) moved downward for a 1 square mile area (gpd/mi^2) at the center of the cone of depression in Savannah. Eight to 10 miles from the center of pumping where the hydraulic-head difference across the upper confining unit was -50 ft, the calculations showed that the downward leakage would be about 9,800 gpd/mi^2. Counts and Donsky (1963) concluded that the rate of saltwater movement through the upper confining unit was small compared to lateral movement in the Upper Floridan aquifer and would have little effect on the quality of water in the aquifer.

Furlow (1969) studied the economic potential for mining phosphate from the upper confining unit in eastern Chatham County, Ga. As part of this investigation, he estimated the potential impact that dredging would have on water quality in the underlying Upper Floridan aquifer if the top section (approximately 40 to 50 ft) of the upper confining unit was removed. Fifty-two cores from the upper confining unit were collected and analyzed to obtain an average hydraulic conductivity of 9.6×10^{-3} gpd/ft^2. Assuming that 40 ft of upper confining unit sediments would remain after dredging, and given a -15-ft average head difference across the upper confining unit, Furlow used Darcy's Law to calculate that downward saltwater migration would occur at a rate of about 160 gallons per acre per day (gal/acre/day) or 102,400 gpd/mi^2. Furlow (1969) stated that even without dredging, saltwater was currently migrating downward at a similar rate. Because of the volume of water contained in the aquifer and the rate of water pumped from the aquifer (63 Mgal/d), however, Furlow (1969) concluded that the quality of water in the Upper Floridan aquifer at the City of Savannah would remain unchanged.

Hayes (1979), Smith (1988), and Garza and Krause (1992) also investigated the downward flow of freshwater through the upper confining unit as part of their investigations related to recharge of the Upper Floridan aquifer. In addition to freshwater recharge, Smith (1988) addressed, in part, the downward migration of saltwater.

Hayes (1976) used Darcy's Law to calculate an average flow of freshwater moving downward through the upper confining unit to the Upper Floridan aquifer in the study area of Beaufort, Jasper, Hampton, and Colleton Counties, S.C. Input parameters for the upper confining unit were an average hydraulic conductivity of 1×10^{-4} feet per day (ft/d), an average thickness of 40 ft, and a downward hydraulic head gradient of 1 ft across the upper confining unit. Hayes (1976) concluded that freshwater from the surficial aquifer was moving downward through the upper confining unit and contributing approximately 5 to 10 Mgal/d (2.86×10^{-4} gpd/mi^2) of recharge to the Upper Floridan aquifer within the study area.

Smith (1988) constructed a steady-state groundwater flow model of the Upper Floridan aquifer in Beaufort and Jasper Counties, S.C. The simulated groundwater budget computed by the model for the region, which included parts of Georgia, indicated that downward vertical leakage accounted for 90 cubic feet per second (ft^3/s), or about 50 percent of the total inflow of 178 ft^3/s to the Upper Floridan aquifer. In the study area of Beaufort and Jasper Counties, S.C., the simulated water budget showed that downward vertical leakage accounted for 46 ft^3/s, or about 66 percent of the total inflow of 72 ft^3/s.

Garza and Krause (1992) constructed a groundwater flow model of the Upper Floridan aquifer that encompassed Chatham, Effingham, Bryan, and Liberty Counties, Ga., and Beaufort and Jasper Counties, S.C. The model simulated a water budget that indicated a downward vertical leakage of 52 Mgal/d compared to a total discharge of 118 Mgal/d. Therefore, the downward flow accounted for 44 percent of the total flow recharging the Upper Floridan aquifer.

Hughes and others (1989) used Darcy's Law to calculate the downward migration of saltwater through the upper confining unit beneath Port Royal Sound northeast of Hilton Head Island. Their work was based on laboratory values obtained for hydraulic conductivity and porosity of cores retrieved from the upper confining unit beneath Port Royal Sound. Using an average hydraulic conductivity of 0.006 ft/d, an average upper confining unit thickness of 30 ft, and a vertical head difference of 1 ft across the upper confining unit, they calculated a volume of 39,400 gpd/mi^2 leaking through the upper confining unit beneath Port Royal Sound. Additionally, they used an average porosity value of 45 percent for the upper confining unit to calculate the bulk volume of water, in cubic feet per square mile (ft^3/mi^2), to be displaced before overlying saltwater could penetrate the total thickness of the upper confining unit and enter the Upper Floridan aquifer. Based on a bulk volume of 376,000,000 ft^3/mi^2 to be displaced at a rate of 5,270 cubic feet per day per square mile ($ft^3/d/mi^2$), Hughes and others (1989) concluded that it would take 200 years for saltwater to enter the aquifer; excluding the effects of dispersion, which would decrease the time to enter the aquifer. A similar calculation was performed for the south end of Hilton Head Island where the upper confining unit had an average thickness of 60 ft and, since 1944, an average head difference of -10 ft across the upper confining unit. In this area, the resulting transit time was estimated to be 40 years, indicating that chloride may have already reached the top of the Upper Floridan aquifer.

Smith (1994) constructed a solute-transport model for the Upper Floridan aquifer beneath Port Royal Sound and simulated the lateral and downward migration of saltwater toward the northern shoreline of Hilton Head Island. The simulated flow for 1984 conditions indicated that saltwater was migrating through the upper confining unit at the rate of 19 centimeters per year (7.48 inches per year) near the shoreline of Port Royal Sound and Hilton Head Island. Smith noted that the model incorporated existing data and followed theoretical concepts, but no chloride concentration data were available in the upper confining unit to confirm the presence or movement of freshwater, brackish water, or saltwater.

Acknowledgements

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Special appreciation is extended to Drennan Park, South Carolina Department of Natural Resources (SCDNR), Robert E. Faye, USGS (retired), W. Barclay Shoemaker, USGS Florida Integrated Science Center, and John Clarke, USGS, Georgia Water Science Center, for providing technical review and discussion. The support of the USGS, Office of Ground Water, Ground Water Resources Program, in particular Paul Barlow, also is appreciated. Paul M. Bradley of the USGS, South Carolina Water Science Center, assisted with laboratory analyses.

Study Area

The study area is located in the Coastal Plain physiographic province of southern South Carolina and northeastern Georgia (fig.1). To the northeast, the study area is bounded by Port Royal Sound, S.C., to the southwest by St. Catherine's Sound, Ga., and to the southeast by the Atlantic Ocean. The main metropolitan areas are Hilton Head Island, S.C., and Savannah, Ga. Hilton Head Island has been developed primarily as a resort community for retirees and tourism whereas the City of Savannah has promoted tourism and industrial development. The topography is generally flat and geographic features include the Atlantic Ocean, saltwater marshes, rivers, estuaries, and freshwater wetlands.

Geology

Sediments that originated from terrestrial, marginal marine, and marine environments underlie the study area; these sediments consist of sands, clays, clayey sands, shells or shell fragments, and carbonates. The unconsolidated sediments form a stratigraphic wedge that thins to a few feet near the Fall Line and thickens toward the coast where the sediments extend to a depth of 3,800 ft below ground surface (bgs) at the southern end of Hilton Head Island (Temples and Waddell, 1996). This investigation focused on the upper 200 ft of sedimentary deposits that include the undifferentiated surficial sediments of Pleistocene and Holocene age, the Hawthorn Group of Miocene age, the Tiger Leap, Suwannee, and Lazaretto Creek Limestones of Oligocene age, and the Ocala Limestone of late Eocene age. A representative hydrogeologic correlation chart from the Tybee Reference Site (fig.1) is depicted in figure 2 (Falls and others 2005).

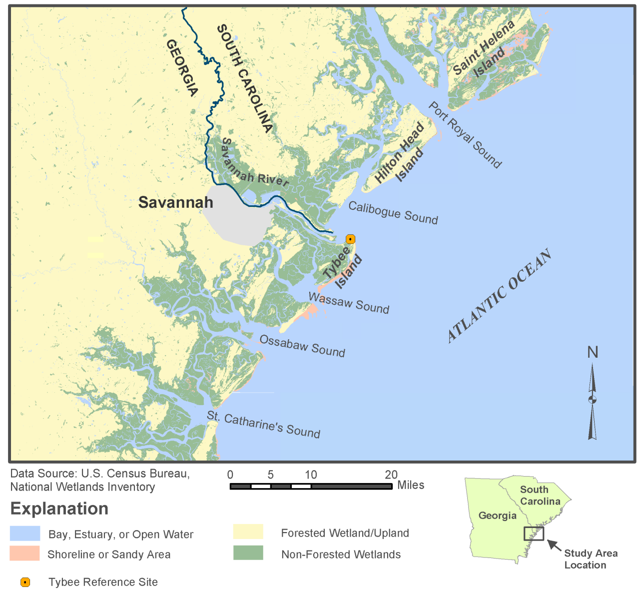


Figure 1. Location of study area, landform classifications, and geographic features.

The surficial sediments are present throughout the study area and consist of interbedded sands, shells, and clays that range from a few feet to 70 ft bgs. Underlying the surficial sediments is the Hawthorn Group comprising three geologic formations. These units are, in order of increasing age, the Coosawhatchie, the Marks Head, and the Parachucla Formations (Huddlestun, 1988). These formations all have an olive green color and consist primarily of fine to medium-grained sand interbedded with silt and clay; some zones contain abundant phosphate. Collectively, the formations making up the Hawthorn Group in the study area range in thickness from 0 to 40 ft to the east and northeast near Hilton Head Island to as much as 150 ft to the southwest near Savannah. Sediments of Oligocene age lie beneath the Hawthorn Group and, where present, are divided into the Tiger Leap, the Suwannee, and Lazaretto Creek Formations (Huddleston, 1988). In the southeastern part of the study area, undifferentiated Oligocene sediments consist of fossiliferous limestone and sandy carbonates. To the northeast, the sediments consist

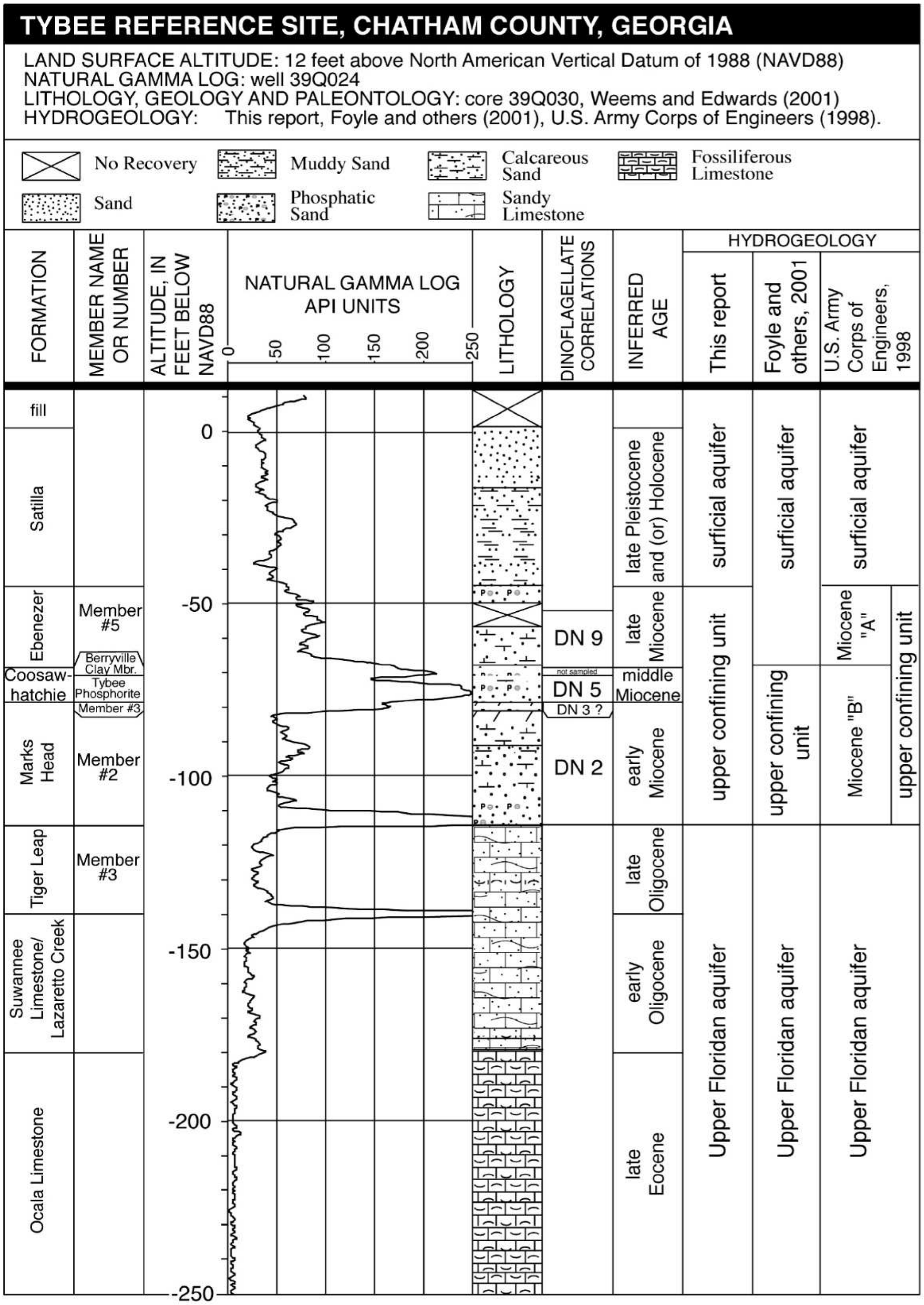


Figure 2. Hydrogeologic correlation chart typical of late Eocene and younger geologic units in the study area (from Falls and others, 2005).

of about 50 percent fine sands embedded in a limy matrix where they eventually thin and pinch out (McCollum and Counts, 1964). The Oligocene sediments are thickest in the southwestern part of the study area near Savannah, where they may be up to 100 ft thick. Recently, Falls and others (2005) documented the Tiger Leap Formation and the Suwannee and Lazaretto Creek Formations to extend offshore from Tybee Island, Ga., to BFT-2258 located 15 miles northeast of Tybee Island. Offshore the Oligocene formations thickened to the northeast.

The Ocala Limestone of Eocene age underlies the Oligocene sediments and is divided into an upper and lower unit (Hughes and others, 1989). The upper unit is a clean, permeable, bioclastic limestone deposited in a shallow marine environment with abundant biological activity. The top of the upper unit ranges in depth from about 40 ft bgs in northeastern Beaufort County to greater than 200 ft bgs near the Savannah River in the southwestern part of the study area (Hayes, 1979; Hughes and others, 1989). The upper unit ranges in thickness from less than 100 ft in the northeastern part of the study area near Hilton Head Island to about 150 ft in the southwest near the Savannah River. The lower unit of the Ocala Limestone was deposited in a deep marine environment and consists of calcite sand with small shell fragments embedded in a limy mud. This unit may be found within the upper 200 ft of sediments in the northeastern part of the study area. Compared to the upper unit, the lower unit has a relatively low permeability (McCollum and Counts, 1964; Hayes, 1979).

Three major structural features have been recognized within the uppermost section of the sedimentary sequence within the study area (fig. 3). Siple (1956) identified a structural high in the limestone strata that he designated the Burton High. This feature was later designated the Beaufort High (Heron and Johnson, 1966) and then the Beaufort Arch (Colquhoun, 1969; Huddlestun, 1988). Furlow (1969) identified another structural high associated with the limestone strata to the southeast of the study area near Tybee Island, Ga.; he designated this area the Tybee High. Further mapping of the limestone strata was conducted by Foyle and others (2001); they collected extensive marine seismic data in the coastal waters of South Carolina and Georgia. Their data supported a structural high offshore from Hilton Head Island that they designated the Hilton Head High. The work of Foyle and others (2001) supports earlier conclusions that the Beaufort High, the Tybee High, and the Hilton Head High are part of the larger Beaufort Arch that had been mapped by Woolsey (1976) along the inner continental shelf as far south as Cumberland Island, Ga.

Surficial sediments and sediments of the Hawthorn Group that overlie the Beaufort Arch are relatively thin because of erosion or lack of deposition. Erosion is evidenced by paleochannels that have been identified throughout the study area by geologic samples and by seismic reflection surveys conducted in local rivers and the Atlantic Ocean (Foyle and others, 2001). In some parts of the study area, paleochannels have incised through the sediments of the Hawthorn Group exposing the underlying carbonate sediments.

Figure 3. Isopach map illustrating structural features and the thickness of the upper confining unit (modified from Miller, 1986; Hughes and others, 1989; and Foyle and others, 2001. Zero contour from Peck and others, 1999).

Hydrogeology

In the South Carolina and Georgia Coastal Plain, geologic strata are grouped into either aquifers or confining units based on the ability to store and transmit water. The primary hydrogeologic units of interest in the study area are the surficial aquifer, the upper confining unit, and the Upper Floridan aquifer.

Surficial Aquifer

The surficial aquifer consists of sands and clays in the upper 50 to 70 ft of sediments in the study area. The quality of water in the aquifer is generally fresh where the landforms are above sea level. In areas where landforms are below mean sea level, such as saltwater marshes, tidal rivers, and the Atlantic Ocean, the aquifer contains saltwater. Recharge to the surficial aquifer is by local precipitation and surface water bodies, and discharge occurs both downward to underlying sediments and laterally to adjacent surface-water bodies.

Upper Confining Unit

The upper confining unit is present throughout the study area and includes the relatively impermeable sediments of the Hawthorn Group and also may include parts of Oligocene carbonates (Miller, 1986). The term “relative” is used because these sediments slow but do not impede the flow of water. When the hydraulic gradient across the upper confining unit becomes greater than a few feet over large geographical areas, the sediments are sufficiently permeable to transmit large volumes of water either upward or downward, depending on the magnitude and direction of the hydraulic gradient. Further support of the upper confining unit’s capability to transmit water can be seen in regional groundwater flow models used to simulate heads in the Upper Floridan aquifer in response to pumping patterns in the study area. The model designs require large volumes of groundwater to move downward through the upper confining unit for simulated heads to obtain a close match with observed heads.

The photograph in figure 4 shows a core section retrieved from the upper confining unit beneath Port Royal Sound, S.C. The high percentage of sand visually observed in the magnified (10X) view of the core compares favorably with the average particle size of sediments analyzed in the laboratory by the USACE for 28 core samples retrieved from the upper confining unit beneath the Savannah River. The analyses showed an average particle size of 67 percent sand, 14 percent silt, and 17 percent clay (Appendix A). The high percentage of sand present in the unconsolidated sediments of the upper confining unit also indicates that the upper confining unit could easily transmit large volumes of water given the groundwater conditions known to occur in the study area.

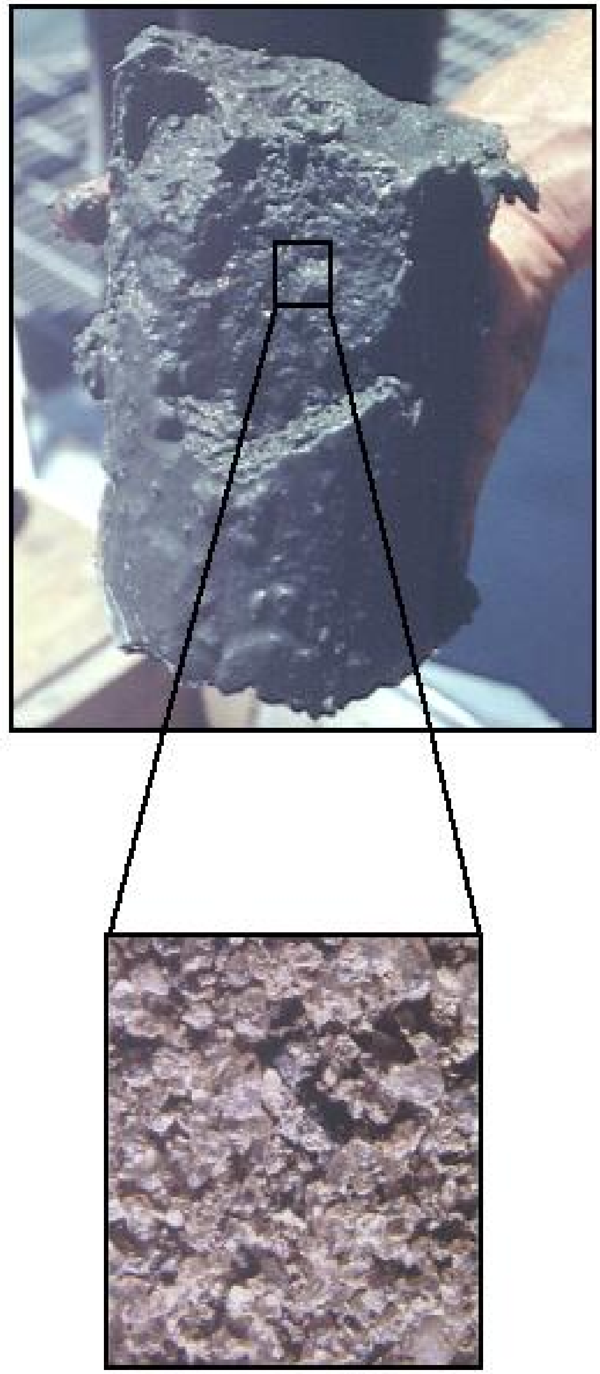


Figure 4. Photograph of core (10X) retrieved from the upper confining unit beneath Port Royal Sound - typical of the upper confining unit in the study area (photograph by C. Ransom, III, 1988).

Upper Floridan Aquifer

The Upper Floridan aquifer underlies the upper confining unit and includes parts of the Oligocene carbonates and the upper unit of the Eocoene Ocala Limestone. The aquifer is the primary source of water in the Savannah – Hilton Head Island area.

Prior to 1880, groundwater flowed from the southwest and west toward the northeast and discharged in the vicinity of Port Royal Sound and the Atlantic Ocean. Discharge also occurred upward through the overlying upper confining unit into surficial strata. The presence of upwelling "boils" of fresher groundwater on the surface of a quiescent saltwater body was reported by early European sailors (Counts and Donsky, 1963), and the translation of the Native American word for Calibogue Bay located near Hilton Head Island as meaning "deep spring" (Landmeyer and Belval, 1996) provide additional anecdotal evidence to support this occurrence. Warren (1944) estimated the potentiometric surface of the Upper Floridan aquifer in the Savannah – Hilton Head Island area in 1880 prior to development. The predevelopment map (fig. 5) shows that groundwater levels ranged from about 35 ft above mean sea level in the vicinity of Savannah to about 10 ft above mean sea level on Hilton Head Island.

In the Savannah area, pumping began in the early 1880's, and by 1888, pumping had increased to 7 Mgal/d. Between 1880 and 1943, groundwater pumpage increased to 42 Mgal/d in the Savannah area (Krause and Clarke, 2001) and the groundwater level declined to approximately 100 ft from predevelopment levels at the center of the cone of depression. By 1957, groundwater withdrawals in the Savannah area had increased to 62 Mgal/d creating a large cone of depression centered at Savannah. Total water-level declines exceeded 120 ft near Savannah and declines of 10 ft were measured 25 miles to the northeast on Hilton Head Island (Counts and Donsky, 1963). Peak withdrawals occurred in 1990 when the reported permitted use was 88 Mgal/d (Clarke and others, 2004). By 2000, groundwater withdrawals had decreased to approximately 70 Mgal/d (Fanning, 2003). Withdrawals from the Upper Floridan aquifer on Hilton Head Island began in the mid 1960's and by 1976 had increased to 8.5 Mgal/d (Hayes, 1979). In 1984, permitted withdrawals had increased to 9.5 Mgal/d (Smith, 1988) and by 1987 had reached 13.3 Mgal/d (McCready, 1989). From 1987 to 2001, permitted groundwater withdrawals continued to increase and peaked at approximately 14.5 Mgal/d. After 2001, alternative supplies were implemented on Hilton Head Island, and reported water use for permitted wells decreased to near 10 Mgal/d. The combined groundwater withdrawals for the Savannah – Hilton Head Island area peaked in 1990 at approximately 102.5 Mgal/d. Afterwards, pumpage decreased and by 1998, groundwater withdrawals in the area were approximately 86 Mgal/d.

The 1998 potentiometric map (Peck and others, 1999) shows that the potentiometric surface had declined below mean sea level for an area covering approximately 2,300 mi^2 (fig. 6). Within the influence of the cone of depression,

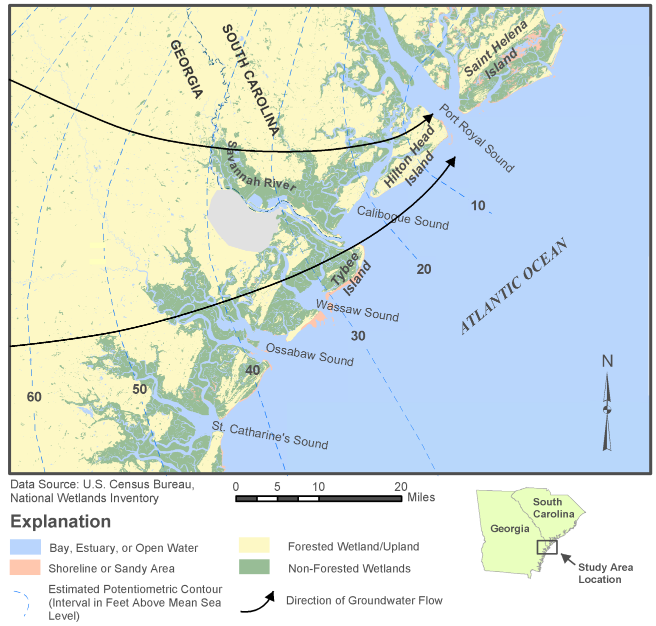


Figure 5. Estimated potentiometric surface of the Upper Floridan aquifer and direction of groundwater flow prior to 1880 (after Warren, 1944).

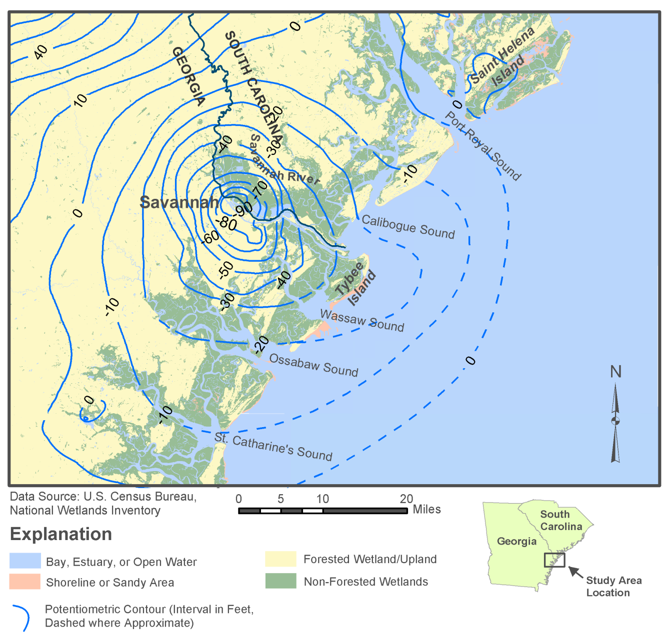


Figure 6. The potentiometric surface of the Upper Floridan aquifer, May 1998 (Modified from Peck and others, 1999).

these water-level declines have reversed the natural groundwater gradient since the 1940's. Groundwater in the Upper Floridan aquifer now flows toward Savannah from all directions and the original upward component of flow through the upper confining unit into the overlying surficial sediments is now downward.

Prior to groundwater withdrawals from the Upper Floridan aquifer in the study area, freshwater discharged upward into surficial sediments and laterally into Port Royal Sound and the Atlantic Ocean thereby providing a hydraulic barrier that prevented saltwater from intruding into the freshwater aquifer. Since the 1950's, however, saltwater intrusion into the Upper Floridan aquifer has been occurring in the study area because groundwater withdrawals have lowered water levels below mean sea level reversing the flow of freshwater into saltwater bodies. This process has been further aggravated by local uplift and erosion of the upper confining unit, which has placed the aquifer relatively close to the surface in areas northeast and east of the study area near Hilton Head Island, S.C., and Tybee Island, Ga. The major sources of saltwater contamination to the Upper Floridan aquifer occur primarily from: (1) recent saltwater entering the aquifer where the overlying confining unit is thin or missing, (2) older, unflushed saltwater in the underlying strata moving vertically upward into the aquifer, (3) saltwater migrating slowly downward through the upper confining unit, and (4) both old and recent saltwater moving laterally in the aquifer.

Figure 7. Location of the 7-mile offshore site, Bull River onshore site, SHE-15, and the vertical hydraulic gradient data collection sites, JAS-0440 and JAS-0441.

Methods

Field and laboratory approaches were used to determine to what extent groundwater pumping in the study area had reversed the upward hydraulic gradient across the upper confining unit, and to determine the extent that a downward hydraulic gradient would allow overlying sources of modern day saltwater to migrate through the upper confining unit toward the Upper Floridan aquifer. Data collected in the study area include pore-water geochemistry and point-specific measurements of hydraulic head in the upper confining unit. The primary data used in this investigation were obtained from four drill sites (fig. 7). Pore-water data were obtained from an offshore site located 7 miles northeast of Tybee Island, Ga. (BFT-2249), and an onshore site located near Bull River, hereafter known as the Bull River site. Two additional drill sites (JAS-0440,-0441) were located adjacent to the Savannah River where data were collected to calculate the hydraulic head at selected depths within the upper confining unit.

Pertinent to pore-water data was the need to ascertain that at each site, saltwater was present in the surficial sediments overlying the upper confining unit. This was achieved by selecting an offshore site in the Atlantic Ocean (7-mile site) and an onshore site (Bull River site) surrounded by large areas of saltwater marshes and tidal rivers.

The first drill site selected for pore-water sampling was located in the Atlantic Ocean as a companion project to an offshore USGS investigation, begun in August 1999. The USGS offshore investigation was designed to study the geology and occurrence of saltwater intrusion into the Upper Floridan aquifer in areas where the upper confining unit was suspected to be absent or thin. This investigation was designed to collect pore-water data and study the downward migration of saltwater through a sufficiently thick section of the upper confining unit. Efforts were made to collect pore-water data at each of the four offshore USGS drill sites. Of the four offshore sites drilled, the 7-mile offshore site (fig. 7) best met the following criteria necessary to examine downward migration of saltwater through the upper confining unit because: (1) the site contained the greatest thickness of confining material for pore-water sampling, and (2) the site represented the greatest vertical head difference (difference between mean sea level and the potentiometric head in the Upper Floridan aquifer) across the upper confining unit - estimated to be -17 ft (Falls and others, 2005).

The second site was selected onshore after evaluating four potential drill sites near Savannah. The onshore sites were evaluated by utilizing a direct-push drilling rig operated by the USACE. At each location, a vertical specific conductance profile through the sediments of the surficial aquifer was conducted using a four-pole Wenner array probe (Geoprobe Systems). Cores were collected from the surficial aquifer and from the top of the upper confining unit for pore-water analysis (data not shown). Of the four preliminary onshore locations, the Bull River site on Georgia State Road 80 (fig. 7) was selected for additional study. The Bull River site was selected because:

(1) the pore-water analyses showed a chloride concentration of 7,830 mg/L at a depth of 48 ft below ground surface (bgs), owing to the large expanse of non-forested saltwater wetlands surrounding the location, (2) the relatively shallow depth (55 ft bgs) to the upper confining unit, (3) the potentiometric head of -40 ft below msl in the Upper Floridan aquifer beneath the location resulted in a relatively large vertical head difference across the upper confining unit, and (4) the location on the GaDOT right-of-way allowed easy access for drilling equipment.

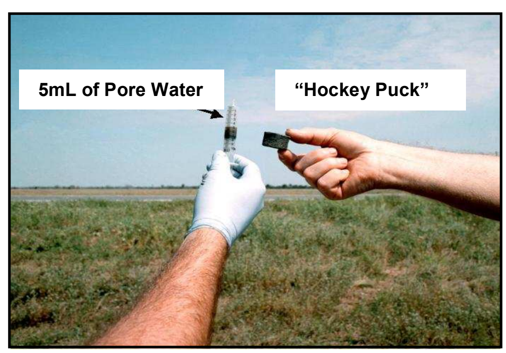
The procedure used to retrieve geologic core from the upper confining unit varied slightly at each location. At the 7-mile offshore site, core material was retrieved by the USACE operating a mud-rotary drilling rig with a double-tube swivel core barrel. The drilling rig was mounted on the USACE's offshore drilling platform "EXPLORER." At the Bull River onshore site, special drilling techniques were required to retrieve continuous, uncontaminated geologic core from the surficial sediments, the upper confining unit, and the underlying Upper Floridan aquifer to a depth of 200 ft bgs. The requirements for retrieving geologic core were achieved using a rotosonic coring rig operated by the Pro-Sonic Corporation (fig. 8a). A rotosonic coring rig generates high frequency vibrations to advance the core barrel and to collect a continuous and relatively undisturbed core without the introduction of drilling fluids. Drilling started by advancing the core barrel, then retrieving and replacing it with 6-inch steel casing placed at 5-ft intervals to maintain the borehole. This process was repeated to a depth of 200 ft. The cores, contained in a lexan liner, were extruded from the core barrel, and a sample of core material was removed by cutting the 5-ft-long core sections in half and removing the sample from the mid-section of each core half to avoid contamination (fig. 8b).

The procedure for extracting pore water and analyzing the water sample to determine the chloride concentration at selected depths was identical at both the 7-mile offshore site and the Bull River onshore site. First, a sediment sample was separated from the geologic core. Afterwards, the sample was immediately placed in an on-site cylinder and piston assembly and pressurized to 1,500 to 3,500 pounds per square inch (psi) using a hydraulic jack (fig. 8c). A syringe connected to an orifice located on the bottom of the piston was used to extract several milliliters of pore water and the compressed sediments appeared similar in shape to a hockey puck (fig. 8d). Chloride concentrations were analyzed at the USGS, South Carolina Water Science Center laboratory using standard ion chromatography methods (DIONEX, 2003).

a. Rotosonic drill rig coring at Bull River

b. Removing core sample from Lexan liner.

c. Placing core sample in cylinder/piston assembly used to squeeze pore water



d. Extracted pore water from compressed

Figure 8. Procedure for extracting pore water at the Bull River site.

Additional support to document the hydraulic gradient across the confining bed was achieved by measuring the difference between the potentiometric head with respect to depth in the upper confining unit. Measurements were taken from two Upper Floridan wells (JAS-0440 and JAS-0441) constructed by the USACE adjacent to the Savannah River, north and northeast of the City of Savannah (fig. 7). Because of the low yield to conventional monitoring wells, pore-pressure transducers of the vibrating wire type were installed between the casing and the borehole wall by the USACE during well construction. Pore-pressure transducers generate pressure data that can be used to determine the magnitude and direction of the vertical gradient. Each transducer was installed on the outer edge of a casing centralizer and connected to the surface with conducting cables. Afterwards, the annular space was filled with neat Portland cement grout to permanently secure and seal the transducers so that only the horizontal component (direction of least resistance) was measured. Vibrating-wire transducers require only a small fluid-volume change (pore-pressure change) for pressure to equalize, therefore the grout can transmit this volume over the short distance from the borehole wall (upper confining unit) to the transducer tip. Pore-pressure data were collected periodically and these point measurements were then converted to hydraulic head (Mikkelsen and Green, 2003).

Results and Discussion

In most reports published since the 1940's, saltwater entering the Upper Floridan aquifer in the Savannah-Hilton Head Island area was assumed to occur primarily from lateral encroachment moving through the aquifer beneath Port Royal Sound toward Hilton Head Island. Back and others (1970) determined that, based on the age of the water tested, the saltwater present in the aquifer was a mixture of unflushed saltwater that had remained for thousands of years where the predevelopment potentiometric surface was near mean sea level, and modern saltwater that had entered the aquifer where the upper confining unit was thin or absent. This investigation focused on the hypothesis that modern saltwater is migrating downward through the upper confining unit regardless of the unit's thickness.

The hypothesis is based on a relatively recent change in the pattern of groundwater flow and how this change has impacted the quality of water in the upper confining unit. Prior to groundwater development in the study area, heads in the Upper Floridan aquifer created an upward vertical hydraulic gradient across the overlying upper confining unit. These heads completely displaced the more dense saltwater that occurred in the sediments at the time of marine deposition. In the late 1930's, however, large increases in groundwater withdrawals from the Upper Floridan aquifer resulted in the development of a cone of depression that encompassed an area of approximately 2,300 mi^2 where the potentiometric surface was below mean sea level. As a result, the pattern of groundwater flow was reversed and the hydraulic gradient across the upper confining unit was downward. This condition allowed overlying saltwater, present in 1,200 mi^2 of marshes, tidal rivers, and the Atlantic Ocean, to migrate downward through the upper confining unit and into the Upper Floridan aquifer.

Pore-water geochemistry was used to trace the occurrence of saltwater in the upper confining unit at two locations in the study area, and two methods were used to further evaluate the downward movement of the saltwater observed in the upper confining unit. The first method applied Darcy's Law to estimate the rate of downward flow and the time required for overlying sources of saltwater to completely displace freshwater throughout the full thickness of the upper confining unit. The second method used a one-dimensional advective-dispersive solute-transport equation to calculate the arrival times for a predetermined chloride concentration to migrate through the upper confining unit to the top of the Upper Floridan aquifer.

Vertical Hydraulic Gradients

Complete displacement in the overlying upper confining unit is supported by the fact that predevelopment heads in the Upper Floridan aquifer remained higher than 5 ft above msl over most of the study area during recent times (fig. 5). Heads were much greater in the past, however, because relative to the current position, mean sea level was approximately 300 ft lower near the end of the last glacial episode approximately 24,000 years ago (Meisler and others, 1984). Only in the extreme northeastern part of the study area have predevelopment heads been near mean sea level in recent times. In this case, the lower freshwater heads in the aquifer would have been insufficient to cause an upward flow and the denser saltwater in the surficial aquifer, in combination with tidal fluctuations and inversion caused by water density, could have moved downward into the underlying upper confining unit (Landmeyer and Belval 1996).

The region-wide reversal of groundwater flow in the study area caused by large groundwater withdrawals can be demonstrated by measuring the vertical hydraulic gradient in the upper confining unit. The magnitude of the vertical head gradient observed is dependent on (1) the vertical hydraulic conductivity (K'_v) of the upper confining unit, (2) the thickness of the upper confining unit, and (3) the difference in head between the Upper Floridan aquifer and the overlying surficial aquifer. The head in the upper confining unit was measured by placing vibrating-wire pore-pressure transducers at two depths in JAS-0440 and at three depths in JAS-0441; both wells were located near the center of the cone of depression (fig.7). The potentiometric head in the Upper Floridan aquifer was manually measured in both wells and these heads were compared to the head measurements calculated from the overlying pore-pressure transducers that were installed adjacent to the upper confining unit (fig. 9). The potentiometric heads at both locations showed a downward hydraulic gradient, indicating that water was moving from the overlying surficial aquifer through the upper confining unit and into the Upper Floridan aquifer. For example, at JAS-0440 located closest to the center of the cone of depression near Savannah, the downward hydraulic gradient was -0.59 across the full thickness of the upper confining unit, and at

JAS-0441 located the greatest distance from the center of the cone of depression, the downward hydraulic gradient was -0.33. Calculating the hydraulic head for incremental sections of the upper confining unit where head data are available shows that the hydraulic gradient is greatest at the bottom section of the confining unit and decreases upward. For example, at JAS-0440, the hydraulic gradient across the upper confining unit for the bottom 40 ft is -1.35 as opposed to -0.59 for the full thickness, and at JAS-0441, the hydraulic gradient across the upper confining unit for the bottom 18 ft is -0.78 as opposed to -0.33 for the full thickness.

Pore-Water Analyses

The 7-mile offshore site and the Bull River onshore site (fig. 7) were chosen for study because these sites provided the most ideal conditions to investigate the potential for saltwater migration through the upper confining unit. The geology at the Bull River onshore site is used herein to describe the sediments that characterize both sites and most of the study area. Analysis of continuous geologic core obtained at the Bull River onshore site indicates that the upper section of surficial sediments consists of alternating beds of sand, clay, and shell fragments to a depth of 55 ft bgs. The surficial sediments are underlain by 20 ft of coarse quartz sand that extends to a depth of 75 ft bgs. This coarse sand deposit is interpreted as a paleochannel that incised through part of the underlying upper confining unit during a period of low mean sea level. Paleochannels are common throughout the coastal area of Georgia and South Carolina (Foyle and Henry, 2001). The upper confining unit underlies the paleochannel and consists mostly of very fine to medium sand interbedded in a matrix of silt and clay to a depth of 120 ft bgs. The undifferentiated limestone of Oligocene age was found beneath the upper confining unit at 120 ft bgs and consisted of unconsolidated medium to coarse quartz sand interbedded with limey clay and shell fragments and extended to a depth to 192 ft bgs. The Ocala Limestone, found at 192 ft bgs, consisted of large, consolidated shell fragments in a lime matrix that extended to the base of the borehole, which totaled 200 ft bgs.

The pore-water analyses from selected core samples at the Bull River onshore site and the 7-mile offshore site were studied to determine to what depth chloride concentrations were present through the thickness of the upper confining unit. Chloride concentrations theoretically are dependent on several hydraulic properties that affect the rate and volume of saltwater migration through the upper confining unit. These properties include (1) the thickness of the upper confining unit, (2) the vertical hydraulic conductivity of the upper confining unit, (3) the average head difference across the upper confining unit, (4) the concentration of saltwater present in the sediment overlying the upper confining unit, (5) the effective porosity of the upper confining unit, and (6) the effects of dispersion and diffusion.

At the 7-mile offshore site, located in the Atlantic Ocean, five pore-water samples were collected at selected depths from a 20-ft-thick section of the upper confining the upper confining unit was assumed to be that of

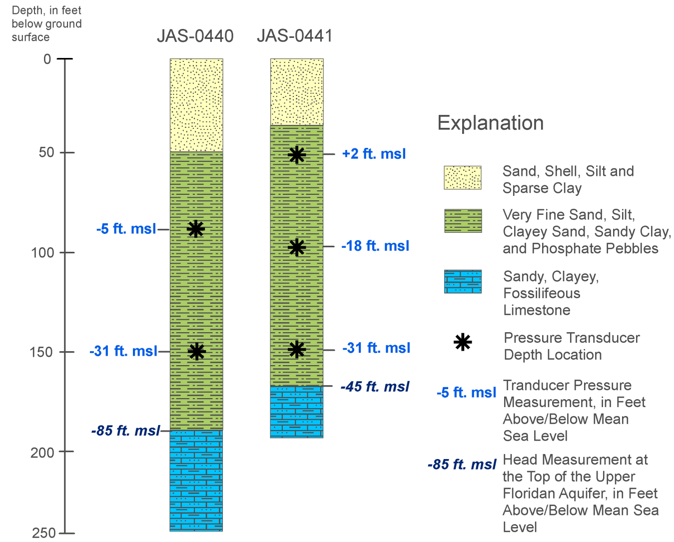


Figure 9. Pressure transducer depth, and hydraulic head data from the upper confining unit and Upper Floridan aquifer from JAS-0440 and JAS-0441. (Pressure transducer data for well JAS-0440 were obtained on October 18, 2001, and data for well JAS-0441 were obtained March 8, 2002).

saltwater (19,000 mg/L). The results of pore-water sample analyses shown in figure 10a indicate that chloride concentrations decreased from 7,034 mg/L near the top of the upper confining unit at -55.5 ft below msl to 2,612 mg/L near the bottom of the upper confining unit at -72.0 ft below msl. After the well was completed in the Upper Floridan aquifer, a water sample was collected 10 ft below the upper confining unit in the Oligocene limestone using a pump rated at 7.5 gallons per minute (gpm). After pumping for 3 hours, the chloride concentration was 370 mg/L (Falls and others, 2005). The pumped sample indicates that saltwater present in the upper confining unit has migrated downward into the top of the Upper Floridan aquifer. At the Bull River onshore site, 23 pore-water samples were collected at 5-ft intervals from the surficial sediments to the top of the Upper Floridan aquifer at 120 ft bgs. Six samples were collected in the aquifer between depths of 122.5 ft and 195 ft bgs (Fig. 10b). Chloride concentrations in the surficial sediments ranged from 121 mg/L near the surface at a depth of 7.5 ft bgs and increased to the maximum concentration of 17,088 mg/L at a depth of 27.5 ft. The low chloride concentrations near the surface are likely the result of freshwater from recent rainfall overlying the more dense saltwater at depth. From a depth of 27.5 ft bgs, chloride concentrations gradually decreased to 8,953 mg/L at a depth of 52.5 ft. An exception occurred in the coarse-grain paleochannel located between depths of 55 ft and 75 ft bgs. Within this interval, the chloride concentration of pore water ranged between 709 mg/L and 3,751 mg/L, much lower than those concentrations present above and below the paleochannel. The lower concentrations may have been the result of contamination by freshwater used to prevent the casing from overheating during drilling operations. The freshwater could possibly have migrated through the more porous paleochannel deposits and diluted the in-situ water with a lower chloride concentration. Locating a new hole 20 ft from the original core site provided an opportunity to test this theory, by using the USGS direct-push rig to advance an open drill rod into the paleochannel sediments. Afterwards, a peristaltic pump was used to extract a sample of groundwater from the bottom of the drill rod at a depth of 62.5 ft bgs. Prior to sampling, water quality was monitored using a specific conductance probe to ascertain that the water was representative of the paleochannel. The laboratory analysis of the sample yielded a chloride concentration of 8,200 mg/L, closely matching the concentrations above and below the paleochannel. Beneath the paleochannel, chloride concentrations decreased with depth through the thickness of the upper confining unit from 7,898 mg/L at a depth of 75 ft bgs near the top of the upper confining unit to 50 mg/L at a depth of 117.5 ft bgs near the bottom of the upper confining unit. Geophysical logs from the Bull River site (Appendix B) provided additional insight into the vertical distribution of chloride. The electrical resistance log shows little change across the borehole intervarepresenting the paleochannel; however, resistance gradually increases with depth through the upper confining unit, an indication that the concentration of chloride is decreasing. Six pore-water samples obtained from the top of the Upper Floridan aquifer between depths ranging from 122.5 ft and 195 ft bgs indicated that chloride concentrations ranged from 17 mg/L to 95 mg/L with an average concentration of 40 mg/L. These concentrations are similar to those found by Clarke and others (1990) who reported that chloride concentrations in the uppermost part of the Upper Floridan aquifer near the Bull River site were 40 mg/L as opposed to background concentrations of less than 10 mg/L in Chatham County. The higher chloride concentration found at the top of the Upper Floridan aquifer in the vicinity of the Bull River site probably resulted from downward migration of saltwater because the upper confining unit is relatively thin in this area.

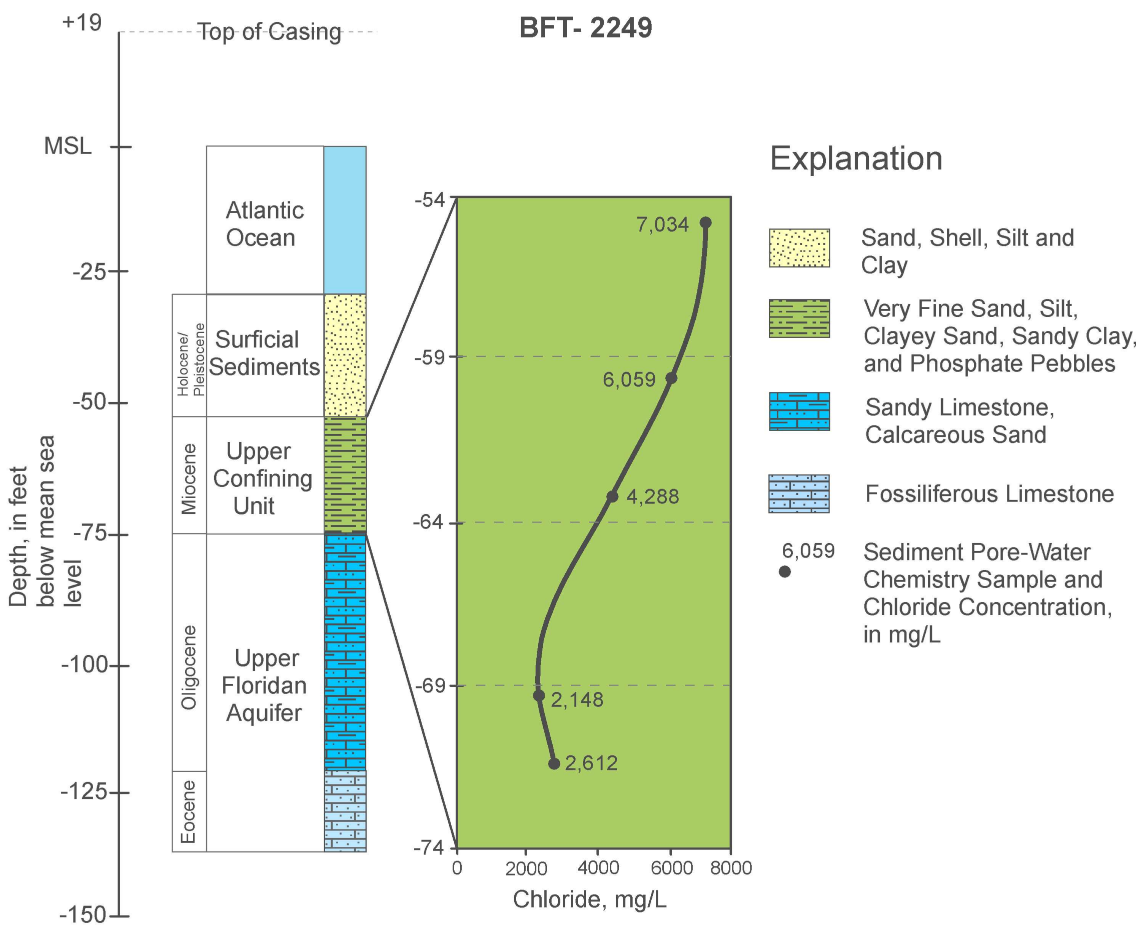


Figure 10a. Pore-water chloride concentrations with depth through the upper confining unit at the 7-mile offshore site (BFT-2249).

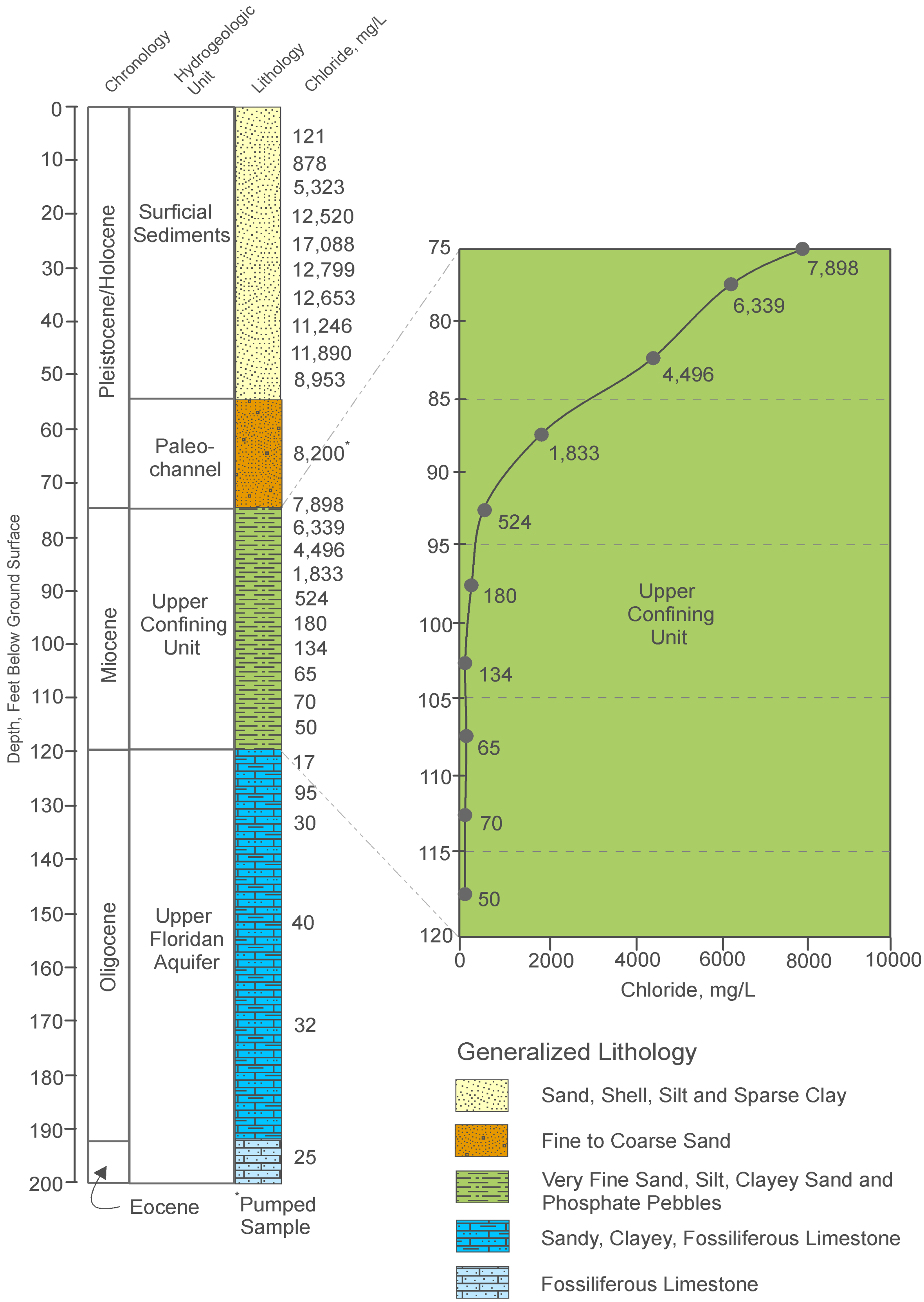


Figure 10b: Pore-water chloride concentrations with depth at the Bull River Site.

The importance of documenting the complete flushing of saltwater in the upper confining unit resultinf from an upward hydraulic gradient prior to groundwater development was discussed earlier. Additional supporting evidence can be obtained by comparing the pore-water chloride profile at the Bull River site with the chloride profile obtained by the USACE and the USGS at SHE-15 located in the Savannah River approximately 1 mile northwest of the Talmadge Bridge (fig. 7). Both wells used pore-water analyses to obtain water-quality data at selected depths within the upper confining unit. The chloride profile at the Bull River site showed higher concentrations than the chloride profile at the SHE-15 site on the Savannah River (Appendix C). This fact is important, because predevelopment estimates of the upward hydraulic gradient across the upper confining unit at the Bull River onshore site and SHE-15 were 0.63 and 0.23, respectively. If saltwater had remained in the upper confining unit because of incomplete flushing, then higher concentrations of chloride would be expected in areas where the predevelopment gradient across the upper confining unit was less. Instead, these data indicate the opposite.

The patterns shown in figures 10a and 10b provide the first evidence that present-day saltwater from surficial sources has moved through the upper confining unit and entered the top of the Upper Floridan aquifer.

Downward Vertical Flow

Darcy's Law (Darcy 1856) is an equation that can be used to estimate the volume of downward groundwater flow through the upper confining unit (fig. 11). Darcy's Law typically is used to describe the flow of fresh groundwater, but was used in this investigation to estimate the flow of saltwater, where present, through the upper confining unit under the assumption that this would be comparable to the bulk advective flow of freshwater. This assumption was tested using the method described in Baxter and Wallace (1916). In their method, replacing the gradient, i, in figure 11 with the following, can simulate the effect, if any, of increased density on groundwater flow,

$$i = \Delta H/\Delta T + \Delta\rho/\rho_{FW} \quad (1)$$

where $\Delta\rho = \rho_{SW} - \rho_{FW}$,

ρ_{SW} = density of saltwater (1,025 kilograms per cubic meter (kg/m^3))

ρ_{FW} = density of freshwater (1,000 kg/m^3).

For example, if the ΔH = 10 feet, and ΔT = 30 feet (representative of conditions across the middle of Hilton Head Island), and if saltwater is migrating downward instead of freshwater, then the calculated gradient (i) will increase from 0.334 under freshwater conditions to 0.358 with saltwater. Therefore, use of the Darcy Law equation for these conditions is defensible in the study area because the change in density has a negligible effect on the flow rate because of the relatively high hydraulic gradients. If the hydraulic gradients were smaller (1 ft or less), however, then the affect of saltwater density becomes important.

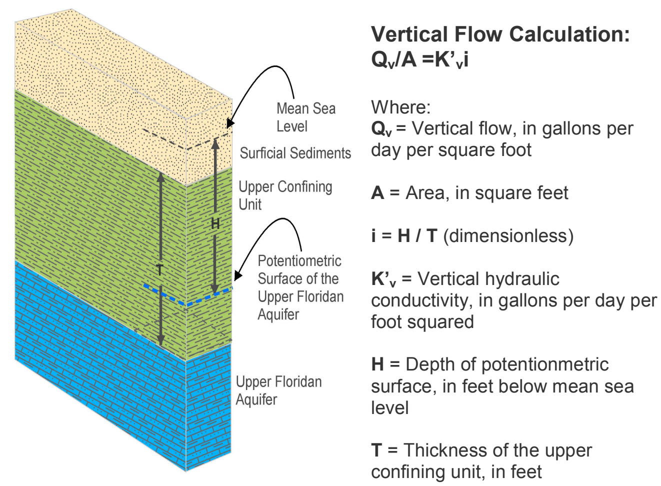


Figure 11. Generalized formula used to calculate vertical flow through the upper confining unit.

The effects of dispersion and diffusion on saltwater migration are not considered herein because they are assumed to be minimal under the high hydraulic gradients known to occur in the study area.

To address changes in the hydraulic gradient, a grid composed of square cells representing 2 miles per side (Appendix D) was superposed over the southeastern part of the cone of depression within the 0-ft potentiometric contour (fig. 6). This grid includes a cell area of approximately 1,255 mi^2 where saltwater is assumed to be present in overlying surficial sediments. To each cell where saltwater was assumed to be present in the overlying surficial sediments, a value was assigned to the upper confining unit for head difference, thickness, and vertical hydraulic conductivity. Darcy's Law was then applied to each grid cell to estimate the volume of downward flow through the upper confining unit into the Upper Floridan aquifer.

Head difference values assigned to each cell (Appendix D) were based on the potentiometric map of the Upper Floridan aquifer that represented conditions during May 1998 (Peck and others, 1999, fig. 6). Head differences at cells superposed over saltwater marshes, tidal rivers, and the Atlantic Ocean were assumed to be the difference between mean sea level and the potentiometric head of the Upper Floridan aquifer, without accounting for the greater density of saltwater, the greater average sea levels that occur within tidal estuaries. Estimates of head in offshore locations corresponded closely with data from four temporary offshore wells (Falls and others, 2005).

The average thickness assigned to each cell for the upper confining unit (Appendix D) was estimated from the isopach map illustrated in figure 4. Consideration was not given to surficial clay beds that may overlie the upper confining unit or to areas where the upper confining unit was believed to be absent or less than 10 feet thick because of paleochannels and other erosional features. Rates of downward saltwater migration in areas where the upper confining unit is thin or absent would be considerably faster, probably resulting in direct intrusion of saltwater into the Upper Floridan aquifer.

Vertical hydraulic conductivity (K'_v) of the upper confining unit was determined by an indirect method designed to overcome the uncertainty inherent in the laboratory-derived values for K'_v, and the application of laboratory-derived values obtained from a single point relative to the geographical scale of the study area. Initially, the water budgets presented in the Savannah area steady-state flow model (Garza and Krause, 1992) and the similar flow model for southern Beaufort and Jasper Counties, S.C. (Smith, 1988) were reviewed to subdivide the total inflow of water to the Upper Floridan aquifer. The total inflow is represented by the lateral component of flow through the Upper Floridan aquifer and the downward component of flow (leakage) through the upper confining unit for the study area. The simulated water budget developed by Garza and Krause (1992) indicated that nearly 42 percent of the total inflow to the Upper Floridan aquifer in the Savannah area resulted from downward leakage. Smith's (1988) simulated water budget for 1984 indicated that about 50 percent of the total inflow resulted from downward leakage in the regional Savannah area. In the study area of southern Beaufort and Jasper Counties, S.C., Smith's simulated water budgets indicated that nearly 64 percent of the total inflow occurred from downward leakage. The increased downward leakage in the study area relative to the region is likely the result of a thin upper confining unit in northeastern part of the study area. Based on the simulated water budgets, average downward leakage from the upper confining unit was estimated to account for up to 50 percent of the total inflow within the 0-ft contour of the cone of depression. A total steady-state pumpage of 80 Mgal/d, estimated to occur in 1998, is partially satisfied by 40 Mgal/d inflow from the southeastern half of the cone of which about 20 Mgal/d (50 percent) is supplied from downward leakage through the upper confining unit. Seventy-five percent or 15 Mgal/d of the downward leakage on the southeastern half of the cone is estimated to move downward from an area totaling approximately 1,200 mi^2 that is overlain by saltwater (fig.12).

Using Darcy's Law (fig.11) to calculate a total downward flow of about 15 Mgal/d occurring within the cells that cover an area of 1,255 mi^2 , an average vertical hydraulic conductivity of $2.4x10^{-3}$ gpd/ft^2 was required. This average value for K'_v was within the range of K'_v values derived from laboratory testing by other investigators and are summarized in Table 1. The most recent data were collected by the USACE (1998), using core material obtained from beneath the Savannah River. The USACE reported K'_v values ranging from $7.1x10^{-5}$ to $4.3x10^{-2}$ ft/d, with an average value of $5.7x10^{-3}$ ft/d (Appendix A). It should be noted that laboratory-derived values for K'_v may be biased low and reflect matrix permeability rather than secondary permeability features (Clarke and others, 2004).

The results indicate that the most substantial downward flow occurs in a 382-mi^2 area overlain by saltwater near Hilton Head Island and extends southwest to Wassaw Sound, Ga. (fig. 13). The total downward flow computed for this area is 7.7 Mgal/d or 51 percent of the total downward flow (15 Mgal/d) occurring over an area of approximately 1,255 mi^2 that is overlain by saltwater. The high downward flow rate results, in part, to high vertical hydraulic gradients across a thin upper confining unit that coincides with the Beaufort Arch, as discussed earlier.

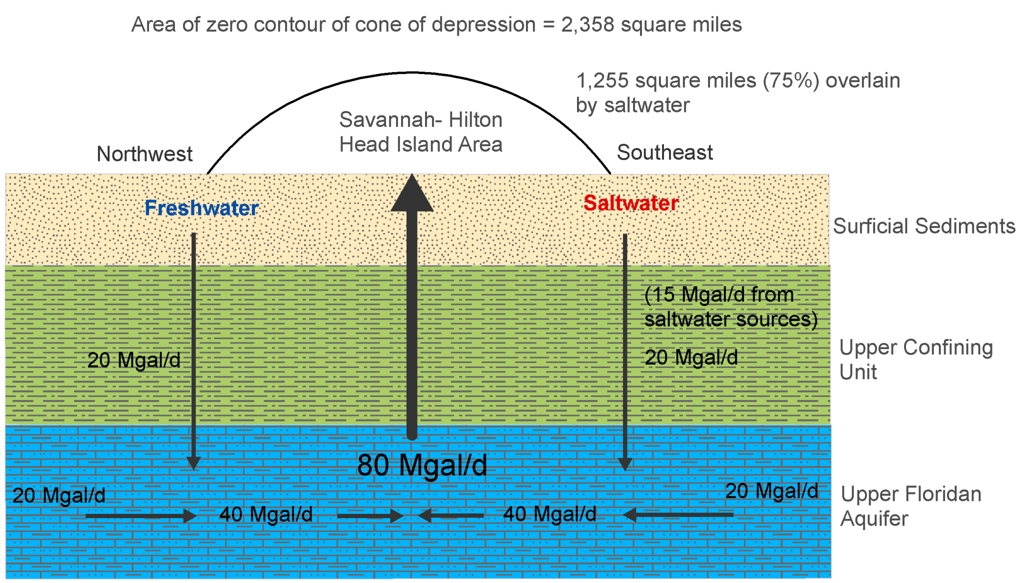


Figure 12. Estimated inflow to the Upper Floridan aquifer based on water budgets from ground-water models (Garza and Krause, 1992 and Smith, 1988).

Table 1. Comparison of published vertical hydraulic conductivity values for the upper confining unit.

Investigators and Date of Publication	Vertical Hydraulic Conductivity (feet per day)	Vertical Hydraulic Conductivity (gpd per ft^2)	Miocene thickness (ft)	Head Difference (ft/ft)
Counts and Donsky (1963)	0.00013	1.0×10^{-3}	150	200
*Furlow (1969)	0.0013	9.6×10^{-3}	40	15
**Hayes (1979)	0.001	1.12×10^{-1}	--	--
Smith (1988) Northern Hilton Head Island Area	0.003	2.24×10^{-2}	--	--
Smith (1988) Port Royal Sound Area	0.006	4.48×10^{-2}	--	--
Hughes and others (1989)	0.006	4.48×10^{-2}	30	1
USACE (1998)	0.0057	4.26×10^{-2}	--	--

*Furlow (1969) reported an average value for vertical permeability, based on 52 core samples, to be 9.6×10^{-3} gpd/ft^2 (0.0013 ft/d). Clarke and others (1990), using Furlow's data, reported vertical hydraulic conductivity values ranged from 5.3×10^{-5} to 1.3×10^{-2} ft/d. **Hayes (1979), based on data from two aquifer tests, reported values for vertical hydraulic conductivity of 1.5×10^{-2} and 5×10^{-3} ft/d; however, he stated that 1.0×10^{-3} ft/d would be a reasonable average value for most of southern Beaufort County, S.C.

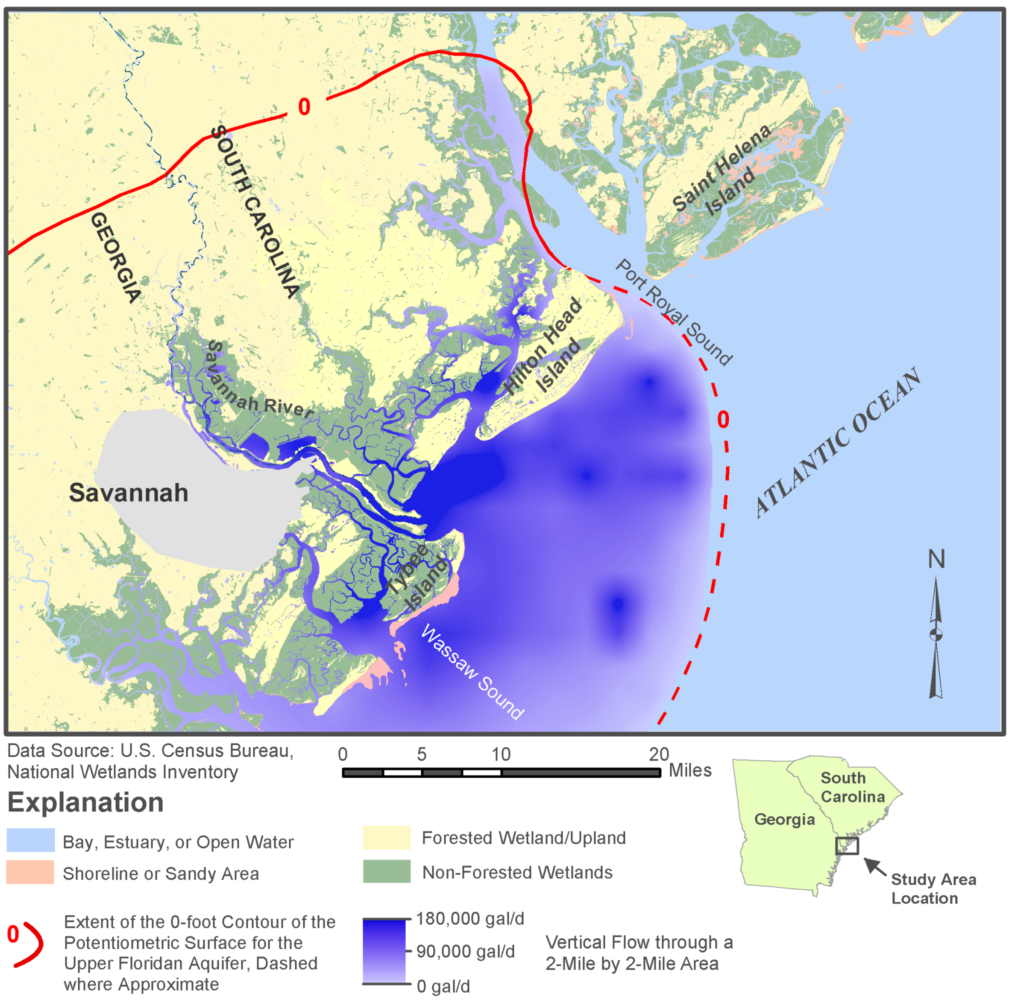


Figure 13. Area showing greatest volume of downward flow through the upper confining unit.

Advective-Dispersive Solute-Transport Model

The potential impact of 7.7 Mgal/d moving downward into the Upper Floridan aquifer in an area covering 382 mi^2 depends on the chloride concentration of the source water and the time needed for the source water to penetrate the upper confining unit. Because the source water disperses as it moves downward, lower chloride concentrations will arrive at the top of the aquifer sooner than arrival by concentrations that represent pure saltwater. The arrival times for increasing concentrations of chloride to move through the upper confining unit and reach the top of the Upper Floridan aquifer were simulated using a numerical form of the one-dimensional advective-dispersive solute-transport equation (Van Genuchten and Alves, 1982; Appendix E) developed by LMNO Engineering, Research, and Software, Ltd. The numerical model was tested for accuracy by using hand calculations starting with the same input data; the results obtained using both approaches agreed, within four decimal places.

Base Case Model

A Base Case model simulating the downward migration of saltwater through the upper confining unit at the Bull River onshore site was developed to provide a reference point for model calibration. The Base Case model was calibrated by adjusting input parameters until an acceptable match was achieved between simulated chloride concentrations and measured chloride concentrations obtained at selected depths. The calibration process used the trial-and-error method to adjust the magnitude of vertical hydraulic conductivity (K'_v), the number of years the simulation runs represented for average 1998 conditions (hydraulic gradient), effective porosity (n_e), and dispersivity (a) and diffusivity (D*). Figure 14 shows the simulated chloride concentrations at selected depths compared to the measured chloride concentrations at the Bull River site. A close match was achieved between simulated and measured chloride values, resulting in a root-mean square error of less than 5 percent of the saltwater source at the top of the upper confining unit (8,200 mg/L chloride). The Base Case model supported the following values for each parameter for the upper confining unit; vertical hydraulic conductivity of 1.5×10^{-3} gpd/ft^2, diffusion of 6.45×10^{-9} ft^2/s, dispersivity of 0.1 ft, effective porosity of 35 percent, and hydraulic gradient of 0.778. It should be noted that to obtain the best match, the value for hydraulic conductivity varied only slightly from the average value (2.4×10^{-3} gpd/ft^2) determined by Darcy's Law for the study area. This is the first time that the vertical hydraulic conductivity of the upper confining unit has been estimated using a modeling approach that was calibrated to the measured chloride profile in the upper confining unit.

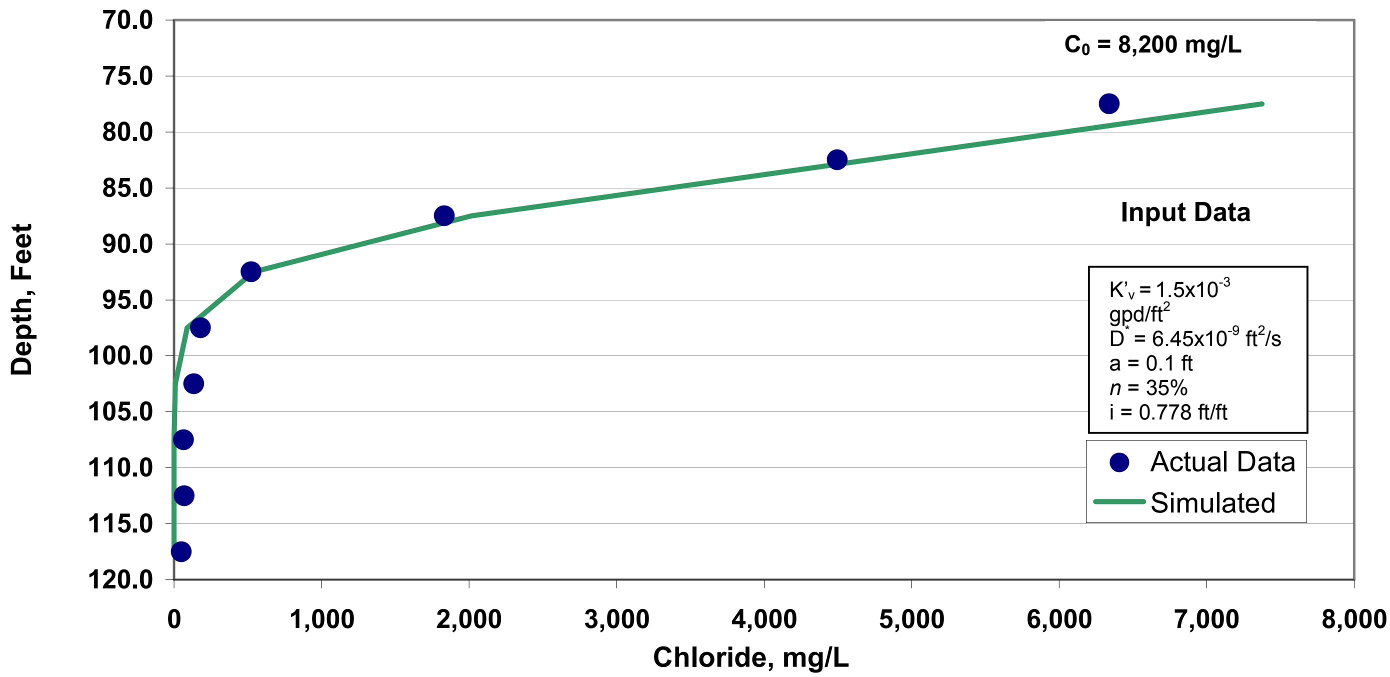


Figure 14. Correlation between measured pore-water chloride concentrations and simulated values for the Bull River site. (Input Data are defined in Appendix E).

Sensitivity Analysis

Sensitivity of the Base Case model to hydraulic properties of the upper confining unit was determined by varying selected parameters one at a time while keeping other parameters unchanged. If a given property can be varied across a wide range of values that extend beyond those commonly accepted with little effect on model results, then the model is insensitive to that property; therefore, the uncertainty inherent in knowing the accurate value of that property is less important. If, however, a given property is varied only slightly, and this variation results in a large change in model results, then that property becomes important to the model. The sensitivity analysis provides important information as to the accuracy of the data to be collected and the construction of the conceptual model.

The sensitivity analyses (Appendix F) showed that the model was sensitive to all properties referenced above. The effect of diffusion on the simulated chloride distribution was investigated by varying the diffusion coefficient from the Base Case of 6.45×10^{-9} to 6.45×10^{-8} and 6.45×10^{-10} ft^2/s; a decrease in the diffusion coefficient from the Base Case reduced the depth of chloride penetration, whereas an increase in D^* increased the depth of chloride penetration. Dispersivity was deviated from the Base Case model of 0.1 ft to 1 and 10 ft. There was little change between simulated values for chloride concentration at depth for dispersivity values of 0.1 and 1 ft, but a substantial change occurred in the simulated values when dispersivity was increased to 10 ft. The higher dispersivity resulted in higher simulated concentrations of chloride to be present at depths that were characterized by lower measured concentrations. Effective porosity was deviated from the Base Case model of 35 percent to values ranging between 25 and 55 percent. Effective porosity values of 45 and 55 percent resulted in simulated chloride concentrations less than those measured at selected depths. Conversely, the lowest simulated effective porosity value of 25 percent resulted in simulated values of chloride higher than those measured at selected depths. The higher chloride concentrations were the result of lower effective porosity and increased rate of solute movement as described in Provost and others (2006). The vertical hydraulic conductivity was deviated from the Base Case model of 1.5×10^{-3} gpd/ft^2 to 2×10^{-3} and 3×10^{-3} gpd/ft^2. The small change in K'_v resulted in a large change in simulated chloride concentrations, which increased at a given depth with a higher value for K'_v. The gradient was varied from the Base Case model of 0.778 to 0.5 and 1.0 ft/ft (no figure shown). A low gradient resulted in lower simulated chloride concentrations at depth than measured, and a high gradient resulted in greater simulated chloride concentrations at depth than measured.

Downward Saltwater Migration

The calibrated, Base Case model was applied to each cell within a 382 mi^2 area to estimate the time for chloride having a concentration of 500 mg/L to reach the top of the Upper Floridan aquifer. The selected model area corresponds to 110 cells of the grid used in the Darcy's Law computations. The calibrated parameters of the Base Case model remained unchanged except for the vertical hydraulic gradient, vertical hydraulic conductivity, and the source concentration. The vertical hydraulic gradient in the Base Case model was the gradient previously assigned at each cell to accommodate Darcy's Law to compute the downward flow through the upper confining unit. The vertical hydraulic conductivity was changed slightly from 1.5×10^{-3} gpd/ft^2 in the Base Case to 2.4×10^{-3} gpd/ft^2 to represent the average value previously calculated for the Darcy Law computations. The concentration of the source (saltwater) was assumed to be 19,000 mg/L chloride (Hem, 1970).

The simulated results are shown on figure 15. The red-shaded cells total 382 mi^2 and represent those areas where the simulated arrival time for chloride with a concentration of 500 mg/L to reach the top of the Upper Floridan aquifer is 113 years or less. Arrival times in the red-shaded cells ranged from 25 years ago (negative values in fig. 15) to 113 years into the future from 2005. Outside of the red-shaded cells, simulated arrival times are much later because of decreasing head differences across the upper confining unit, increasing thickness of the upper confining unit, or a combination of both. The 382 mi^2 area is considered an area of concern, because of the high downward flow rates and the relatively short arrival time for water containing 500 mg/L of chloride to enter the top of the Upper Floridan aquifer. The simulated arrival time for water with an average chloride concentration of 500 mg/L to enter the top of the Upper Floridan aquifer beneath the area of concern is about 36 years from 2005. Assuming that 50 percent of the total flow is from downward leakage and that the remaining 50 percent is from lateral flow within the aquifer, then mixing would result in a total flow of about 15.4 Mgal/d with an average chloride concentration of 250 mg/L. The simulation results indicate that average chloride concentrations will continue to increase and at a more rapid rate with respect to time (fig. 16). For example, the average chloride concentration will increase to 1,000 mg/L in 48 years and to 2,000 mg/L in 72 years from 2005.

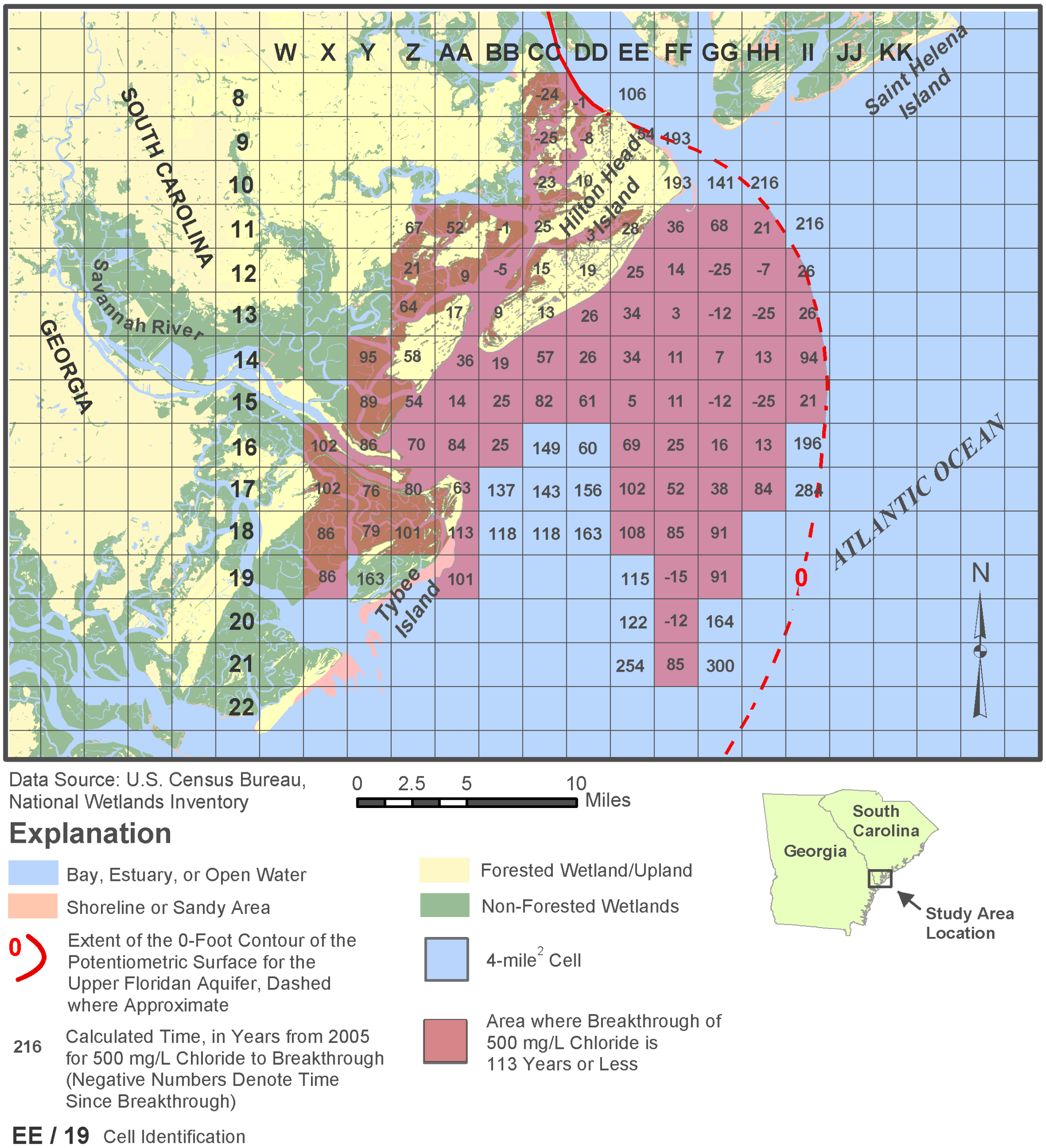


Figure 15. Estimated time, in years from 2005, for 500 mg/L chloride concentration to arrive at the top of the Upper Floridan aquifer.

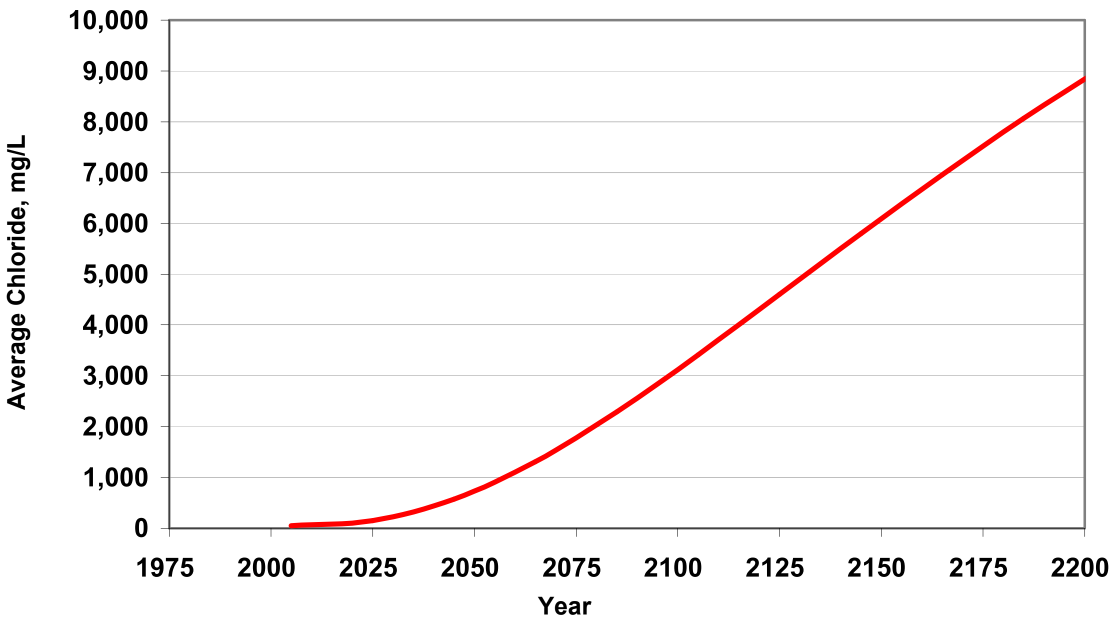


Figure 16. Simulated arrival time for average chloride concentrations to enter the top of the Upper Floridan aquifer from the upper confining unit beneath the area of concern northeast of Savannah, Georgia.

Limitations of the Mathematical Model

Generally, there are two classifications of models in groundwater hydrology, conceptual models and mathematical models. A conceptual model represents a hypothesis about flow in a real or natural system. In order to quantify relations in a conceptual model, a mathematical model can be designed to simulate groundwater flow by itself or with solute transport. Physical properties (parameters, such as vertical hydraulic conductivity or porosity) and processes (flow or transport) are represented as mathematical equalities and equations. Properties that describe groundwater flow or solute transport, such as head elevation or gradient and solute concentrations, can be physically measured, and are mathematically expressed as variables in the equations. The mathematical models used as part of this investigation were the one-dimensional form of the Darcy flow equation (Darcy's Law as discussed in the "Downward Vertical Flow" section and shown on figure 11) and the one-dimensional advection-dispersion solute-transport equation (Appendix E).

Generally all models (conceptual and mathematical) are limited in representing all of the physical processes involved in a given investigation. The purpose of this investigation was to understand the data collected and their implications for groundwater use in the study area. It was beyond the scope of this investigation to use more physically comprehensive mathematical models that solve three-dimensional variable density groundwater flow and transport, such as SUTRA (Voss, 1984; Voss and Provost, 2002) or SEAWAT (Guo and Langevin, 2002; Langevin and others, 2003). Thus, this section of the report fully describes the limitations of the models developed for this investigation and how errors in properties and parameters used in the models effect the calculated results. The two results of interest from this investigation were the estimated vertical flow through the upper confining unit in areas overlain by saltwater (fig. 13) and the estimated time for the saltwater to move through the upper confining unit (fig 15).

The one-dimensional transport equation is related to the one-dimensional Darcy flow equation in that the pore velocity (V_w) of the solute transport equation is equal to the Darcy velocity divided by the porosity of the material. In the Darcy equation for vertical flow, vertical hydraulic conductivity and flow are directly correlated, which means that if vertical hydraulic conductivity of the upper confining unit is increased, then the flow through the upper confining unit is increased. Additionally, the gradient is directly correlated to the flow. In the one-dimensional form of the equation the flow means that the Darcy velocity is downward. Because the pore velocity is equal to the Darcy velocity divided by porosity, then an error in estimating the Darcy velocity directly translates to an error in estimating the pore velocity. The pore velocity of the transport equation is inversely proportional to the porosity, which means that if the porosity of the upper confining unit is decreased, the calculated pore velocity of the upper confining unit would increase. Thus, it is critical to understand the uncertainty in the parameters and properties used in the Darcy velocity estimate that is then used in the one-dimensional advection-dispersion solute-transport equation that is used to estimate the time for saltwater to move through the upper confining unit.

The method for estimating K'_v and thus, the vertical Darcy velocity was fully described in the section "Downward Vertical Flow." However, some of the inherent uncertainty of the indirect estimate of K'_v will be more fully described here. The total flux estimated through the upper confining unit is based on gross groundwater flow model water budgets that indicate that roughly 50 percent of the pumped groundwater from the Upper Floridan aquifer is derived from vertical leakage through the upper confining unit. It was assumed that half of this leakage (20 Mgal/d) is over the southeastern half of the area defined by the 0 contour on figure 12 and that 75 percent of this (15 Mgal/d) leaks in the area overlain by saltwater. Spreadsheets were created to break the area into 4-mi^2 cells (2 mi on each side length) and the head difference and confining unit thickness calculated for each cell (Appendix D). The indirect K'_v required to match the estimated flux through the system using Darcy's law was 2.4×10^{-3} gpd/ft^2, which was within the range of previously determined K'_v. However, if the initial flux through the system (a percent of estimated 1998 pumpage) was overestimated, then the indirectly estimated K'_v would be overestimated, and if the initial flux was underestimated, then K'_v would be underestimated. Error in estimating the 1998 head difference and clay thickness in each cell would also result in error in the estimation of K'_v. It was shown that the effect of ignoring density of the saltwater above the upper confining unit has the effect of underestimating the actual pressure gradient measured. In the example shown, the pressure gradient with density included in the computation was 7 percent higher than the gradient computed without density. Additionally, it is almost a certainty that K'_v varies both geographically and with depth. Given all of the uncertainty associated with estimating K'_v and using only one value of K'_v for the study area, the effect of ignoring density in this simplified approach is defensible. Readers are cautioned that the estimated downward flow of 7.7 Mgal/d over the 382 mi^2 area overlain by seawater is not an exact estimate. For example, if the range in K'_v (table 1) is applied, the range in vertical downward flow from the Darcy approach ranges from 3.2 to 144 Mgal/d. The highest previously published value for K'_v (table 1) cannot be considered reasonable in this simplified method for estimating downward flow, as this value results in an estimated downward flow greater than the total pumpage for the region in 1998. The blue-shaded rates of vertical flow shown in figure 13 should not be considered exact rates either. The relative rates of vertical flow, however, are more than likely reasonable in that the areas with highest vertical flow are in areas where the upper confining becomes thinner (although still thicker than 10 ft) and/or the head difference is greatest (the gradient is large).

As can be seen from the above discussion, there is uncertainty to the Darcy velocity calculated for each 4 mi^2 cell in the one-dimensional, advection-dispersion solute-transport equation used to estimate the time of travel for saltwater to move through the upper confining unit (fig. 15). The sections "Advective-Dispersive Solute-Transport Model" and "Base Case Model" discussed the calibration and sensitivity analysis of the one-dimensional advection-dispersion solute-transport equation (Appendix E) that was calibrated to chloride data collected from the upper confining unit at the Bull River site. The transport model solves for chloride concentration over time at various depths given a value of pore velocity (calculated from gradient multiplied by vertical hydraulic conductivity divided by effective porosity), diffusion, dispersivity, and the length of time that the chloride is "injected" or in this case that the gradient became reversed.

The degree that one parameter in the groundwater flow or solute-transport equation can be varied to determine its affect on model-simulated values is called a sensitivity analysis. If a parameter, such as vertical hydraulic conductivity, can be varied across a wide range of values, which may extend beyond the actual range of known data, with little effect on model-simulated results, then this indicates that the model is insensitive to vertical hydraulic conductivity. This assumes, however, that the other model parameters such as effective porosity are accurately assigned in the sensitivity analysis. Conversely, if a small change in vertical hydraulic conductivity results in a large change in model-simulated results, then it becomes important to collect accurate data for vertical hydraulic conductivity. Regardless of the level of sophistication of a model, sensitivity analyses can provide important guidance regarding the accuracy of the data to be collected as well as the cause and effect relations between model parameters and predicted results. The sensitivity analysis (Appendix F) provides some insight into which of these properties or parameters are more important for matching the observed chloride distribution in the upper confining unit at the Bull River site. The sensitivity analysis was accomplished by changing some parameters by orders of magnitude (dispersivity and diffusion) and other parameters (vertical hydraulic conductivity, effective porosity, and time since the gradient was reversed) by lesser amounts. The sensitivity analysis indicates that errors in vertical hydraulic conductivity, effective porosity, and time since the gradient was reversed have a greater effect on chloride concentration than dispersivity and diffusion. Uncertainty in effective porosity has the greatest effect in that a 10 percent reduction in effective porosity from the calibrated value resulted in approximately as large a change in simulated chloride as the doubling of hydraulic conductivity from the calibrated value. The sensitivity analysis, however, was limited by the non-linearity of the transport equation. With a non-linear equation, the sensitivities of parameters change when the parameter values change. For example, the sensitivity analysis of vertical hydraulic conductivity will not be correct if other parameters, such as effective porosity are incorrect. Even with the limitations of the sensitivity analysis, errors in vertical hydraulic conductivity and effective porosity have the greatest effect on the estimated time that the chloride would move vertically through the upper confining unit, provided that the gradient used is correct (measured values of head and confining unit thickness).

In using the one-dimensional solute-transport equation as described in the “Downward Saltwater Migration” section, requires the assumption that the following properties are uniform over the area: vertical hydraulic conductivity (1.5 x 10^{-3} gpd/ft^2), effective porosity (35%), dispersivity (0.1 ft), and diffusion (6.45 x 10^{-9} ft^2/s). Additionally, these calculations require the assumption that the gradient remains constant and at the same values as in Appendix D (steady-state condition). As previously stated it is unlikely that the upper confining unit properties are uniform across the area. Additionally, the variation in effective porosity is poorly known. Thus, the estimated time in years from 2005 for 500 mg/L chloride concentration to arrive at the top of the Upper Floridan aquifer (figure 15) are not exact numbers and should be treated in a somewhat qualitative manner. The simulated arrival time for average chloride concentrations to enter the top of the Upper Floridan aquifer from the upper confining unit northeast of Savannah, Ga. (fig. 16) should be considered an approximation. While not providing exact numbers, the model does provide useful insights into when and where water quality may start to be affected by saltwater migration through the upper confining unit into the top of the Upper Floridan aquifer.

Summary and Conclusions

The Upper Floridan aquifer is composed primarily of permeable carbonates of late Eocene and Oligocene age, and is the principal source of groundwater in the Savannah, Georgia – Hilton Head Island, South Carolina, area. Sediments of Miocene age overlie the aquifer and consist mostly of fine sand with a silty, clayey matrix. The low permeability of the Miocene deposits act as a confining unit to restrict, but not prevent, the flow of water between overlying sources to the Upper Floridan aquifer.

Prior to 1888, the potentiometric surface in the Upper Floridan aquifer ranged from about 10 to 35 feet above mean sea level in the study area, and groundwater discharged to the northeast into Port Royal Sound and upward through the upper confining unit. By 1960, groundwater withdrawals from the Upper Floridan aquifer were about 63 million gallons per day in Savannah, Georgia, the hydraulic gradient was reversed, and water flowed downward through the upper confining unit into the Upper Floridan aquifer and laterally toward the center of pumping at Savannah. Pumpage continued to increase in Savannah and, with development on Hilton Head Island, totaled about 102 million gallons per day in 1990. Pumpage decreased to about 80 million gallons per day by 1998 and the potentiometric surface ranged from about 90 feet below mean sea level near the center of pumping at Savannah to about 4 feet below mean sea level at the north end of Hilton Head Island.

The combined groundwater withdrawals at Savannah and Hilton Head Island created a cone of depression that encompassed an area of approximately 2,300 square miles within the 0-foot potentiometric contour. Model simulations indicate that, within the 0-foot potentiometric contour of the cone of depression, groundwater is now moving downward through the upper confining unit and into the Upper Floridan aquifer. Based on simulated water budgets from published reports, this report estimates that about 40 million gallons per day, or 50 percent of the total inflow to the Upper Floridan aquifer of 80 million gallons per day, is from downward recharge. Approximately 15 million gallons per day is moving downward within the southeastern part of the cone where the upper confining unit is overlain by approximately 1,200 square miles of saltwater in the form of tidal marshes, rivers, and the Atlantic Ocean. In these areas, saltwater is displacing freshwater as it moves downward through the upper confining unit into the top of the Upper Floridan aquifer. The theoretical rate of displacement through the upper confining unit depends on the thickness, vertical hydraulic conductivity, effective porosity, head difference, dispersion and diffusion, and concentration of brackish or saltwater at the source.

Two sites were selected to evaluate the presence and extent of chloride concentrations in the upper confining unit by extracting pore water from core samples at selected depths. The first site was completed 7 miles northeast of Tybee Island, Georgia, in the Atlantic Ocean, and a second site was completed near Bull River between Tybee Island and the pumping center at Savannah. The chloride concentration in pore water at the 7-mile offshore site decreased from 7,034 milligrams per liter at the top of the upper confining unit to 2,612 milligrams per liter near the bottom of the upper confining unit. Beneath the upper confining unit at the 7-mile offshore site, the chloride concentration in a pumped sample collected 10 feet into the top of the Upper Floridan aquifer was 370 milligrams per liter. At the Bull River onshore site, chloride concentrations decreased from 6,339 milligrams per liter at the top of the upper confining unit to 50 milligrams per liter near the bottom of the confining unit. Beneath the upper confining unit at the Bull River onshore site, chloride concentrations measured from pore water ranged from 17 to 95 milligrams per liter in the top of the Upper Floridan aquifer. Data from both sites indicated that saltwater has moved vertically downward through the confining unit and into the top of the underlying Upper Floridan aquifer.

The estimated rate (in gallons per day) of downward saltwater migration from surficial sources was calculated by applying Darcy’s Law to each 4-square-mile cell superposed over approximately 1,255 square miles within the 0-foot potentiometric contour of the cone of depression. To apply Darcy’s Law, vertical hydraulic gradients for each cell were based on the hydraulic heads estimated from the1998 potentiometric map constructed by Peck and others (1999) and the upper confining unit thickness determined from isopach maps constructed by Miller (1986), Hughes and others (1989), and Foyle and others (2001). A constant value for the estimated average vertical hydraulic conductivity of 2.4x10^{-3} gallons per day per square foot was assigned to each cell. These calculations indicated that an area totaling 382 square miles near Hilton Head Island and Tybee Island, accounted for 7.7 million gallons per day, or 50 percent of the 15 million gallons per day moving downward through the upper confining unit. The relatively large volume of downward recharge to the Upper Floridan aquifer is predominantly the result of a thin upper confining unit that contributes to a high downward hydraulic gradient.

Measurements of chloride concentration in the upper confining unit at the Bull River onshore site were used to calibrate an analytical model based on a one-dimensional advective-dispersive solute-transport equation (Van Genuchten and Alves, 1982). Values for vertical hydraulic conductivity, time (years), effective porosity, dispersion, and diffusion, were adjusted to simulate the measured chloride concentrations for selected depths at the Bull River onshore site. The root-mean square error was less than 5 percent of the source concentration (8,200 milligrams per liter).

The calibrated model was applied to each 4-square-mile cell within the 382-square-miles area overlain by saltwater to simulate arrival times for chloride concentrations of 500 milligrams per liter to reach the top of the Upper Floridan aquifer, assuming 1998 pumping conditions. Within the 382-square-mile area, arrival times ranged from 25 years ago to 113 years into the future (from 2005) with an overall average of 36 years from present (2005). The simulated results indicated that chloride concentrations would increase more rapidly with time.

Assuming that 50 percent (7.7 million gallons per day) of the total inflow within the 382-square-mile cell area was contributed by lateral movement in the Upper Floridan aquifer, mixing 7.7 million gallons per day of downward flow with an average chloride concentration of 500 milligrams per liter may produce a combined volume of about 15.4 million gallons per day with an average chloride concentration of 250 milligrams per liter within about 36 years. Because these conditions could impact the quality of water in the aquifer, this report considered the cell area of 382 square miles to be an area of concern.

The downward migration of saltwater northeast of Savannah may affect groundwater quality in the Savannah – Hilton Head Island area in 50 years or less, from 2005. Chloride concentrations in the aquifer are dilute compared to their probable source, but they are important in light of expected background concentrations and the predevelopment potentiometric surface. Clarke and others (1990) reported an average chloride concentration of less than 10 milligrams per liter in the Savannah area. A.D. Park (South Carolina Department of Natural Resources, oral commun., 2005) observed that, in Beaufort and Jasper Counties, S.C., any chloride occurrence greater than 6 milligrams per liter indicates proximity to a source of contamination. If pumping remains similar to 1998 conditions, then chloride concentrations in parts of the Upper Floridan aquifer will probably exceed 250 milligrams per liter, the maximum limit for secondary drinking-water standard (U.S. Environmental Protection Agency, 1976).

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Appendix A. Summary of Permeability and Index Testing

Boring	Sample	Geol. Unit	Depth	Atterberg Limits		Gravel	Sand	Silt	Clay	Vertical Hydraulic Conductivity	
			(ft)	LL	PI	(%)	(%)	(%)	(%)	(cm/sec)	(ft/d)
SHE-1	1	A	62.3 - 63.9	----	----	0.0	88.2	5.8	6.0	3.4 x 10E-6	9.6 x 10E-3
SHE-1	2	A	67.1 - 68.0	----	----	0.0	88.8	7.3	3.9	3.5 x 10E-6	9.9 x 10E-3
SHE-1	3	B	90.7 - 91.8	----	----	0.0	78.9	6.2	14.7	5.5 x 10E-8	1.6 x 10E-4
SHE-1	4	B	97.1 - 98.2	----	----	0.0	89.2	3.1	7.7	4.5 x 10E-7	1.3 x 10E-3
SHE-2	1	A	57.4 - 58.1	57	23	0.4	74.5	12.1	13.0	4.1 x 10E-6	1.2 x 10E-2
SHE-2	2	A	67.5 – 68.6	60	24	0.2	77.9	16.5	5.4	7.5 x 10E-7	2.1 x 10E-3
SHE-2	3	B	81.6 – 83.0	145	74	2.2	25.2	48.7	23.9	2.8 x 10E-8	7.9 x 10E-5
SHE-2	4	B	97.2 – 98.2	97	47	0.8	66.5	11.3	21.4	5.4 x 10E-8	1.5 x 10E-4
SHE-3	1	A	50.6 – 51.4	----	----	0.0	82.2	7.3	10.5	1.0 x 10E-5	2.8 x 10E-2
SHE-3	2	A	60.3 – 61.4	----	----	0.0	87.6	5.0	7.4	1.8 x 10E-6	5.1 x 10E-3
SHE-3	3	B	80.4 – 81.3	----	----	0.0	69.7	12.7	17.6	5.5 x 10E-8	1.6 x 10E-4
SHE-3	4	B	90.3 – 91.4	----	----	0.0	48.5	25.4	26.1	3.7 x 10E-8	1.0 x 10E-4
SHE-4	1	A	67.2 – 67.7	----	----	0.3	87.5	7.1	5.1	4.7 x 10E-6	1.3 x 10E-2
SHE-4	2	A	75.4 – 76.3	----	----	0.3	89.9	4.1	5.7	1.3 x 10E-6	3.7 x 10E-3
SHE-4	3	B	89.1 – 89.9	----	----	0.0	34.0	28.9	37.1	2.1 x 10E-8	6.0 x 10E-5
SHE-4	4	B	99.8 – 100.5	----	----	0.0	51.1	15.6	33.3	2.5 x 10E-8	7.1 x 10E-5
SHE-5	1	A	64.4 – 65.1	----	----	0.1	37.8	21.0	41.1	1.2 x 10E-7	3.4 x 10E-4
SHE-5	2	A	78.2 – 79.1	----	----	0.0	71.5	10.7	17.8	4.1 x 10E-7	1.2 x 10E-3
SHE-5	3	B	142.8 – 144.0	----	----	0.0	73.4	14.2	12.4	9.4 x 10E-8	2.7 x 10E-4
SHE-5	4	B	151.7 – 152.4	----	----	0.0	87.3	4.5	8.2	4.9 x 10E-7	1.4 x 10E-3
SHE-6	1	CF	68.1 – 69.0	----	----	0.0	11.4	33.9	54.7	3.0 x 10E-7	8.5 x 10E-4
SHE-6	2	A	71.6 – 72.6	----	----	0.0	89.5	5.6	4.9	1.5 x 10E-5	4.3 x 10E-2
SH-65	1	A	79.3 – 80.9	87	27	----	----	----	----	2.2 x 10E-7	6.2 x 10E-4
SH-65	2	A	96.2 – 98.0	59	30	----	----	----	----	6.0 x 10E-7	1.7 x 10E-3
SH-65	3	B	115.8 – 117.2	66	38	----	----	----	----	7.9 x 10E-7	2.2 x 10E-3
SH-318	1	CF	69.9 – 71.3	150	80	----	----	----	----	4.0 x 10E-7	1.1 x 10E-3
SH-318	2	CF	71.3 – 73.5	145	64	----	----	----	----	8.2 x 10E-6	2.3 x 10E-2
SH-327	1	CF	50.5 – 52.5	124	45	----	----	----	----	1.8 x 10E-6	5.1 x 10E-3
Unit A Average						**0.1**	**79.6**	**9.3**	**11.0**	**3.5 x 10E-6**	**9.9 x 10E-3**
Unit B Average						**0.3**	**62.4**	**17.1**	**20.2**	**1.9 x 10E-7**	**5.4 x 10E-4**
Miocene Average (A+B)						**0.2**	**71.4**	**13.0**	**15.4**	**2.0 x 10E-6**	**5.7 x 10E-3**
Channel Fill Average						**----**	**----**	**----**	**----**	**2.7 x 10E-6**	**7.7 x 10E-3**
Over-all Average						**0.2**	**68.7**	**14.0**	**17.2**	**2.1 x 10E-6**	**6.0 x 10E-3**

Notes: A = Miocene Unit A.
B = Miocene Unit B.
CF = Relict Channel Fill.

(Modified from USACE, 1998)

Boring	Sample	Elevation	Geologic Unit	USCS Class	Grain Size Distribution % Gravel	% Sand	% Fines	Porosity	Hydraulic Conductivity $k_{20°C}$ (cm/sec)	Hydraulic Conductivity $k_{20°C}$ (ft/d)
SHE-11	K-1	-30.3	CF	CH	0.0	12.3	87.7	0.692	4.79E-08	1.36E-04
SHE-11	K-2	-57.8	CF	CH	0.0	10.8	89.2	0.691	4.33E-08	1.23E-04
SHE-11	K-3	-60.3	CF	CH*	0.0	4.8	95.2	0.728	5.40E-08	1.53E-04
SHE-13	K-1	-51.6	CF	SC	0.0	81.2	18.8	0.412	2.78E-06	7.88E-03
SHE-13	K-2	-57.4	CF	CH*	0.0	47.4	52.6	0.633	1.46E-07	4.14E-04
SHE-14	K-1	-44.9	CF	CH*	0.0	3.2	96.8	0.662	7.90E-08	2.24E-04
SHE-17	K-1	-40.0	CF	CL	0.0	49.9	50.1	0.582	6.99E-08	1.98E-04
SHE-17	K-2	-44.7	CF	CH*	0.0	40.4	59.6	0.577	6.38E-08	1.81E-04
SHE-17	K-3	-52.3	CF	CH	0.0	28.6	71.4	0.655	6.18E-08	1.75E-04
Mean Values for Channel Fill Material:					**0.0**	**31.0**	**69.0**	**0.626**	**3.72E-07**	**1.05E-03**
SHE-9	K-1	-50.8	A	MH	0.3	13.0	86.7	0.683	1.80E-06	5.10E-03
SHE-9	K-2	-61.5	A	MH	0.0	35.3	64.7	0.711	3.10E-07	8.79E-04
SHE-9	K-3	-80.7	A	SM	0.0	65.2	34.8	0.587	1.50E-06	4.25E-03
SHE-9	K-4	-101.1	A	MH	13.6	22.6	63.8	0.660	4.80E-08	1.36E-04
SHE-9	K-5	-112.2	A	CH	1.3	30.0	68.7	0.664	9.40E-08	2.66E-04
SHE-10	HC-1	-55.1	A	SM	0.1	72.5	27.4	0.629	1.70E-07	4.82E-04
SHE-10	HC-2	-62.4	A	MH	0.0	23.9	76.1	0.747	1.10E-07	3.12E-04
SHE-10	HC-3	-69.5	A	MH	0.8	49.0	50.2	0.709	1.10E-06	3.12E-03
SHE-10	HC-4	-83.9	A	MH	0.0	18.3	81.7	0.688	5.50E-07	1.56E-03
SHE-10	HC-5	-92.5	A	MH	0.0	14.8	85.2	0.718	2.90E-07	8.22E-04
SHE-10	HC-6	-98.6	A	MH	0.0	33.8	66.2	0.709	1.70E-07	4.82E-04
SHE-10	HC-7	-104.5	A	SC	0.0	62.5	37.5	0.581	4.50E-07	1.28E-03
SHE-10	HC-8	-112.0	A	SM	0.0	53.3	46.7	0.774	7.10E-07	2.01E-03
SHE-10	HC-9	-119.5	A	SM	0.0	84.7	15.3	0.504	2.40E-07	6.80E-04
SHE-10	HC-10	-128.5	A	SM	0.0	65.8	34.2	0.456	1.50E-06	4.25E-03
SHE-10	HC-11	-137.5	A	SM	0.0	72.5	27.5	0.464	3.20E-05	9.07E-02
SHE-10	HC-12	-144.4	A	SM	0.0	81.1	18.9	0.458	2.20E-07	6.24E-04
SHE-11	K-4	-70.1	A	SC-H	0.0	80.7	19.3	0.507	2.53E-07	7.17E-04
SHE-11	K-5	-79.6	A	MH	0.0	40.7	59.3	0.507	6.44E-08	1.83E-04
SHE-13	K-5	-74.3	A	CH*	0.0	3.8	96.2	0.662	1.69E-07	4.79E-04
SHE-13	K-6	-79.9	A	CH*	0.0	1.7	98.3	0.688	9.92E-08	2.81E-04
SHE-13	K-7	-83.9	A	MH	0.0	22.8	77.2	0.633	7.32E-08	2.07E-04
SHE-13	K-8	-88.1	A	MH*	0.0	34.3	65.7	0.629	8.81E-08	2.50E-04
SHE-14	K-2	-51.9	A	CH*	0.0	10.8	89.2	0.646	7.39E-08	2.09E-04
SHE-14	K-3	-56.3	A	CH*	0.0	2.1	97.9	0.650	1.58E-07	4.48E-04
SHE-14	K-4	-65.3	A	SP-SM	0.0	94.1	5.9	0.404	1.12E-04	3.17E-01
SHE-15	K-1	-55.0	A	MH	0.0	19.2	80.8	0.712	1.48E-07	4.20E-04
SHE-15	K-2	-63.3	A	MH*	0.0	27.8	72.2	0.636	4.74E-08	1.34E-04
SHE-15	K-3	-72.3	A	CH*	0.0	27.4	72.6	0.671	1.46E-07	4.14E-04

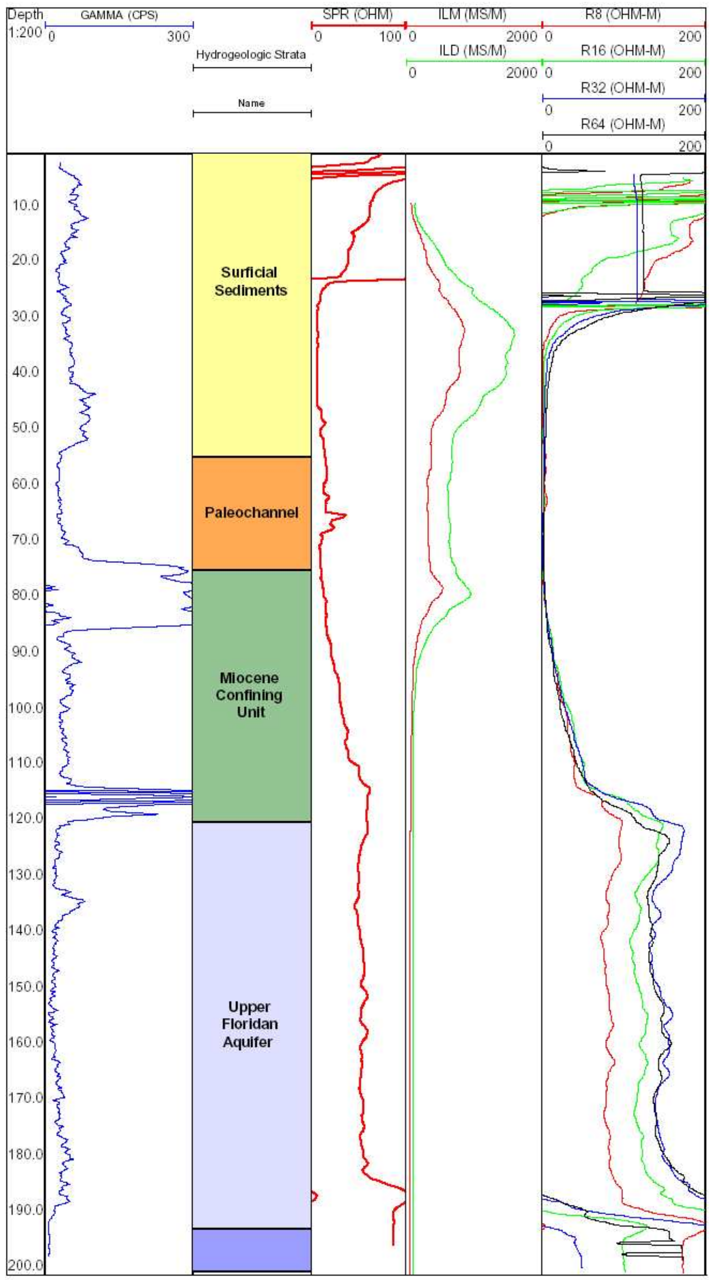
Boring	Sample	Elevation	Geologic Unit	USCS Class	Grain Size Distribution % Gravel	% Sand	% Fines	Porosity	Hydraulic Conductivity $k_{20°C}$ (cm/sec)	Hydraulic Conductivity $k_{20°C}$ (ft/d)
SHE-15	K-4	-83.0	A	SC*	0.0	68.2	31.8	0.572	3.34E-07	9.47E-04
SHE-15	K-5	-95.3	A	OH	0.0	5.3	94.7	0.647	2.44E-07	6.92E-04
SHE-15	K-6	-113.1	A	OH*	0.0	0.4	99.6	0.744	1.84E-08	5.22E-05
SHE-16	K-1	-42.8	A	SC-H	0.0	68	32.0	0.529	6.28E-07	1.78E-03
SHE-16	K-2	-53.8	A	SC*	0.0	83.6	16.4	0.469	7.09E-07	2.01E-03
SHE-17	K-4	-59.2	A	SC-H	0.0	78.6	21.4	0.478	1.04E-06	2.95E-03
SHE-17	K-5	-68.8	A	SP-SM	0.0	88.2	11.8	0.499	2.29E-07	6.49E-04
SHE-18	K-1	-64.5	A	OH	0.0	2.1	97.9	0.817	2.12E-07	6.01E-04
SHE-18	K-2	-70.2	A	SM*	0.0	79.8	20.2	0.494	9.95E-08	2.82E-04
SHE-19	K-1	86.2	A	CH	0.0	48.6	51.4	0.498	3.27E-06	9.27E-03
SHE-19	K-2	96.7	A	MH	0.0	4.4	95.6	0.599	2.61E-06	7.40E-03
SHE-19	K-3	118.5	A	SC-H	0.0	61.6	38.4	0.585	1.41E-07	4.00E-04
SHE-19	K-4	131.8	A	MH*	0.0	48.2	51.8	0.592	6.28E-08	1.78E-04
SHE-19	K-5	142	A	MH	0.0	12.7	87.3	0.638	3.10E-08	8.79E-05
SHE-19	K-6	152.5	A	MH*	0.0	8.5	91.5	0.671	2.58E-08	7.31E-05
SHE-19	K-7	162.3	A	OH	0.0	0.3	99.7	0.761	1.18E-08	3.34E-05
SHE-19	K-8	167.1	A	OH*	0.0	29.7	70.3	0.796	3.15E-08	8.93E-05
Mean Values for Miocene Unit A:					**0.4**	**40.3**	**59.4**	**0.619**	**3.57E-06**	**1.01E-02**
SHE-9	K-6	-129.4	B	SC	0.0	70.0	30.0	0.465	2.80E-07	7.94E-04
SHE-9	K-7	-148.4	B	SM	0.0	73.2	26.8	0.520	1.30E-07	3.69E-04
SHE-9	K-8	-164.2	B	SM	0.0	71.9	28.1	0.540	1.70E-07	4.82E-04
SHE-9	K-9	-175.3	B	SM	0.0	65.7	34.3	0.564	1.40E-07	3.97E-04
SHE-9	K-10	-188.5	B	SM	0.1	68.1	31.8	0.540	2.80E-07	7.94E-04
SHE-10	HC-13	-150.9	B	SM	0.0	77.3	22.7	0.469	2.50E-07	7.09E-04
SHE-10	HC-14	-160.9	B	SM	0.0	66.7	33.2	0.488	1.50E-06	4.25E-03
SHE-11	K-6	-91.1	B	CH*	0.0	0.0	100.0	0.489	6.12E-08	1.73E-04
SHE-11	K-7	-98.8	B	SM*	0.0	79.4	20.6	0.543	9.48E-08	2.69E-04
SHE-11	K-8	-101.1	B	SM-H	0.4	86.0	13.6	0.508	2.37E-07	6.72E-04
SHE-11	K-9	-106.8	B	SM-H	0.0	51.9	48.1	0.663	3.92E-08	1.11E-04
SHE-13	K-9	-93.1	B	MH	0.0	19.2	80.8	0.686	5.44E-08	1.54E-04
SHE-13	K-10	-98.8	B	MH*	0.0	11.0	89.0	0.716	4.88E-08	1.38E-04
SHE-13	K-11	-105.6	B	SM-H	0.0	61.5	38.5	0.612	1.32E-07	3.74E-04
SHE-14	K-5	-71.3	B	MH*	0.0	22.9	77.1	0.582	3.40E-08	9.64E-05
SHE-14	K-6	-76.3	B	SM-H	0.0	51.1	48.9	0.590	1.05E-07	2.98E-04
SHE-14	K-7	-81.3	B	MH	0.0	40.0	60.0	0.634	5.69E-07	1.61E-03
SHE-14	K-8	-86.8	B	SM*	0.0	56.9	43.1	0.593	5.77E-08	1.64E-04
SHE-14	K-9	-92.5	B	SM*	0.0	68.1	31.9	0.616	1.13E-07	3.20E-04
SHE-15	K-7	-135.3	B	SC-H	0.0	68.4	31.6	0.511	6.55E-08	1.86E-04
SHE-15	K-8	-144.7	B	SM-H	0.0	81.9	18.1	0.433	5.74E-07	1.63E-03
SHE-15	K-9	-155.3	B	MH*	0.0	45.3	54.7	0.607	6.64E-08	1.88E-04
SHE-15	K-10	-171.0	B	SM-H	0.0	59.5	40.5	0.586	4.96E-08	1.41E-04
SHE-15	K-11	-181.3	B	SM*	0.0	50.1	49.9	0.611	6.33E-08	1.79E-04

Boring	Sample	Elevation	Geologic Unit	USCS Class	Grain Size Distribution % Gravel	% Sand	% Fines	Porosity	Hydraulic Conductivity $k_{20°C}$ (cm/sec)	Hydraulic Conductivity $k_{20°C}$ (ft/d)
SHE-15	K-12	-193.9	B	SM-H	0.0	66.5	33.5	0.567	4.95E-07	1.40E-03
SHE-16	K-3	-70.1	B	CH*	0.0	43.2	56.8	0.546	2.07E-08	5.87E-05
SHE-16	K-4	-80.1	B	SC-H	0.0	56.0	44.0	0.550	7.26E-08	2.06E-04
SHE-16	K-5	-91.8	B	SM-H	0.0	53.5	46.5	0.579	2.98E-08	8.45E-05
SHE-17	K-6	-86.7	B	MH	0.0	45.4	54.6	0.521	4.87E-08	1.38E-04
SHE-18	K-3	-93.9	B	SM-H	0.0	65.5	34.5	0.603	1.62E-07	4.59E-04
SHE-18	K-4	-106.3	B	SM*	0.0	75.4	24.6	0.541	5.09E-08	1.44E-04
SHE-19	K-9	188.8	B	SM-H	0.0	68.9	31.1	0.430	9.60E-08	2.72E-04
SHE-19	K-10	202.1	B	SM-H	0.0	57.4	42.6	0.565	1.58E-08	4.48E-05
SHE-19	K-11	213.7	B	SM-H	0.0	54.5	45.5	0.478	5.39E-08	1.53E-04
Mean Values for Miocene Unit B:					**0.0**	**56.8**	**43.1**	**0.557**	**1.81E-07**	**5.14E-04**
Mean Values for Miocene Confining Unit:					**0.2**	**47.3**	**52.5**	**0.593**	**2.13E-06**	**6.04E-03**

CF = Channel Fill
A = Miocene Unit A
B = Miocene Unit B
* = Soils visually classified

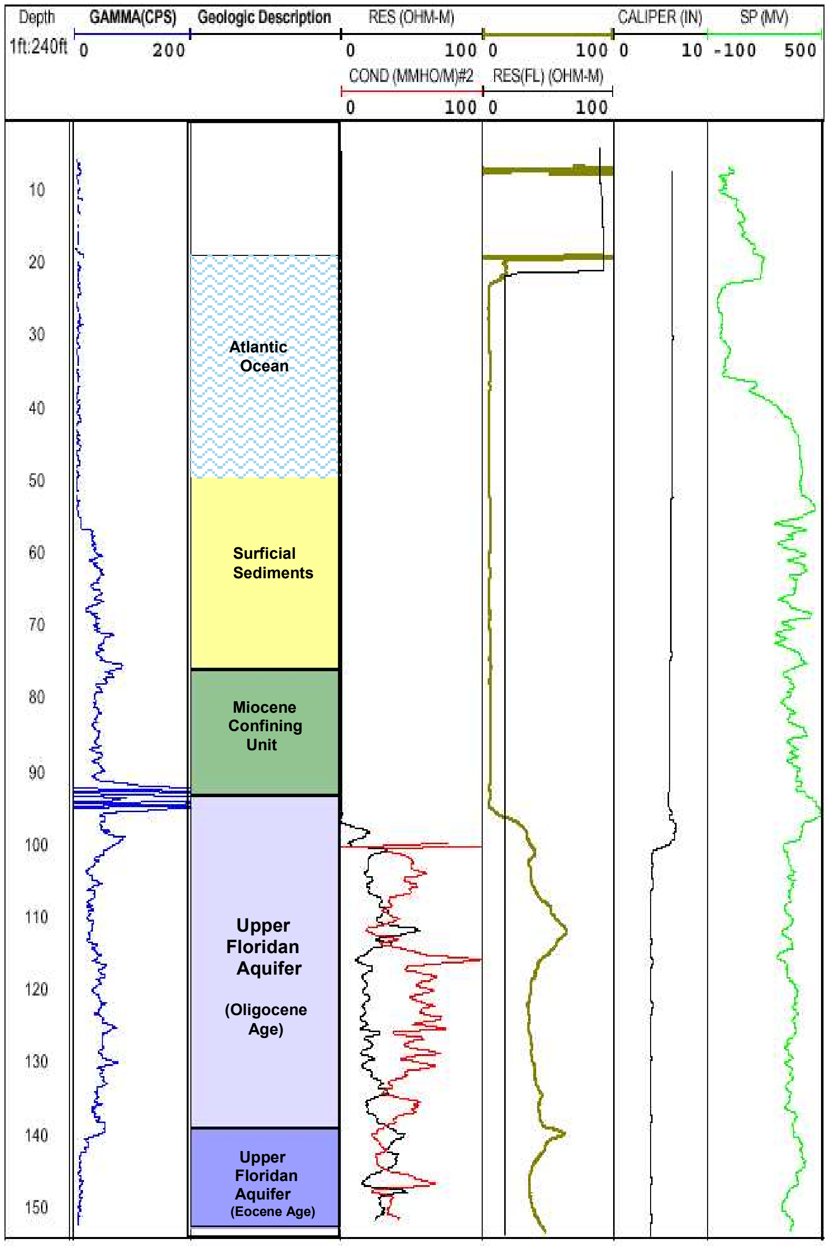
Appendix B Geophysical Logs – Bull River Onshore Site and 7-Mile Offshore Site

Bull River Onshore Site

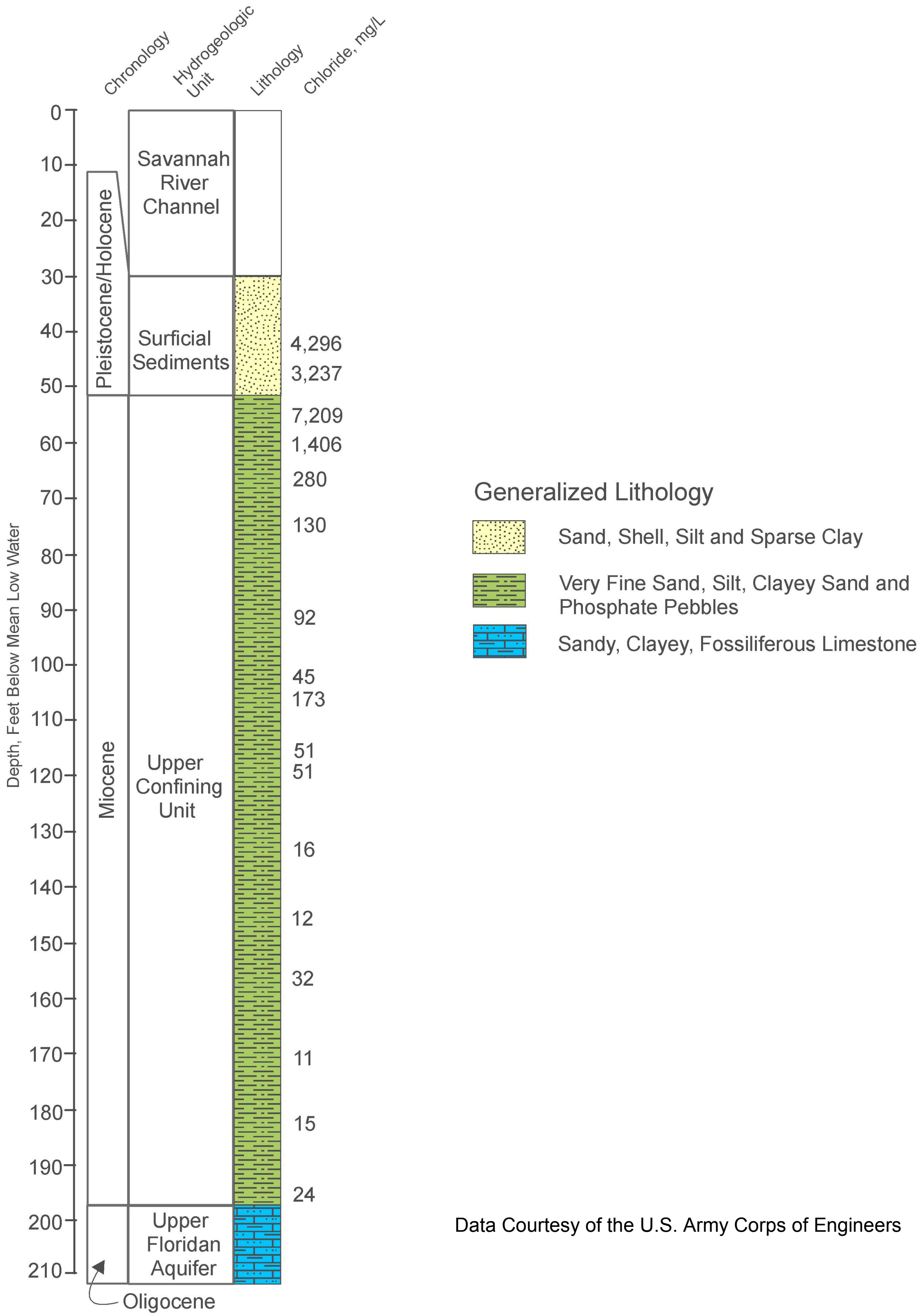


Appendix B. con't

7-Mile Offshore Site

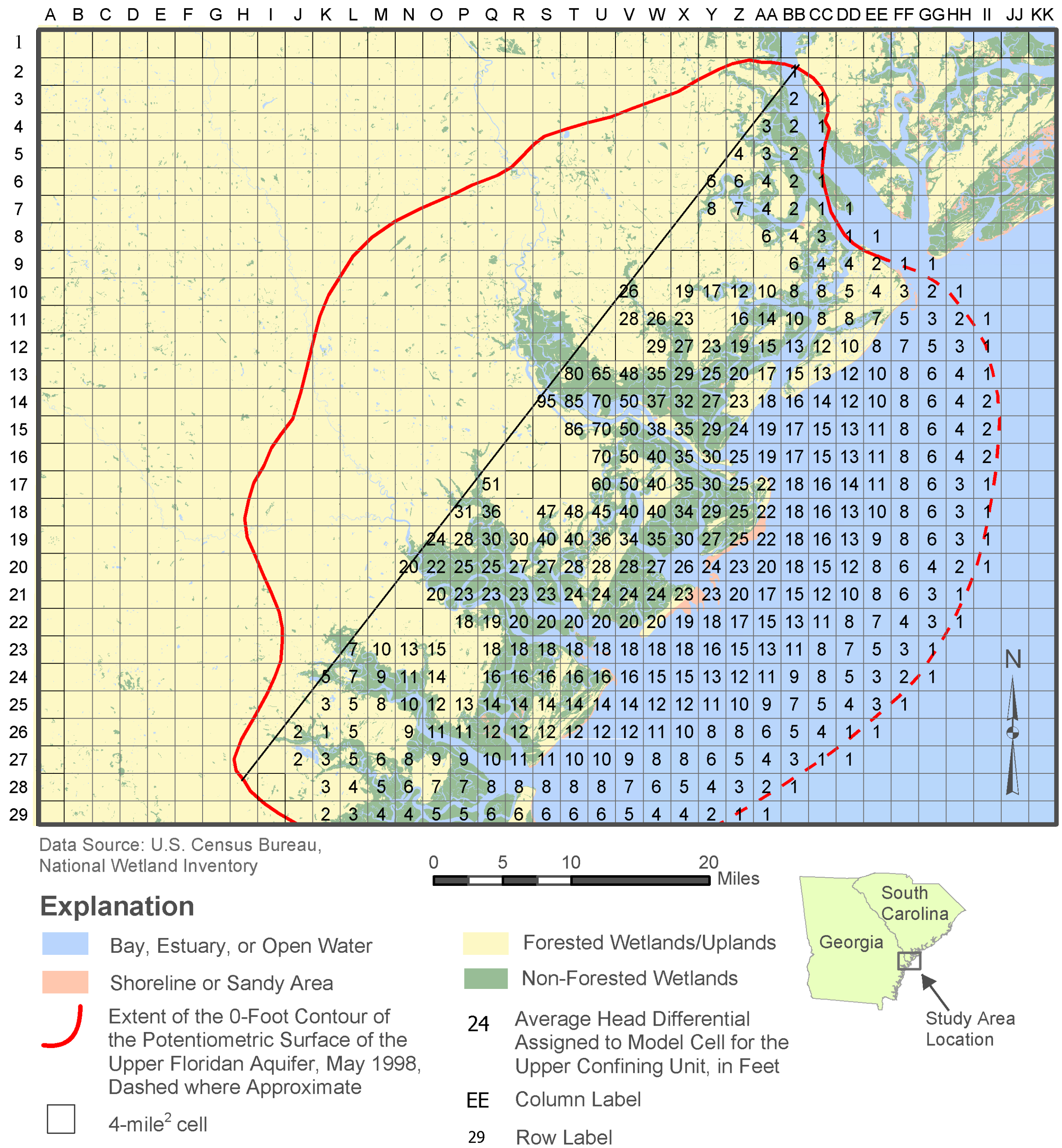


Appendix C. Geologic Log and Pore-Water Chloride Profile of SHE-15, Savannah River Channel



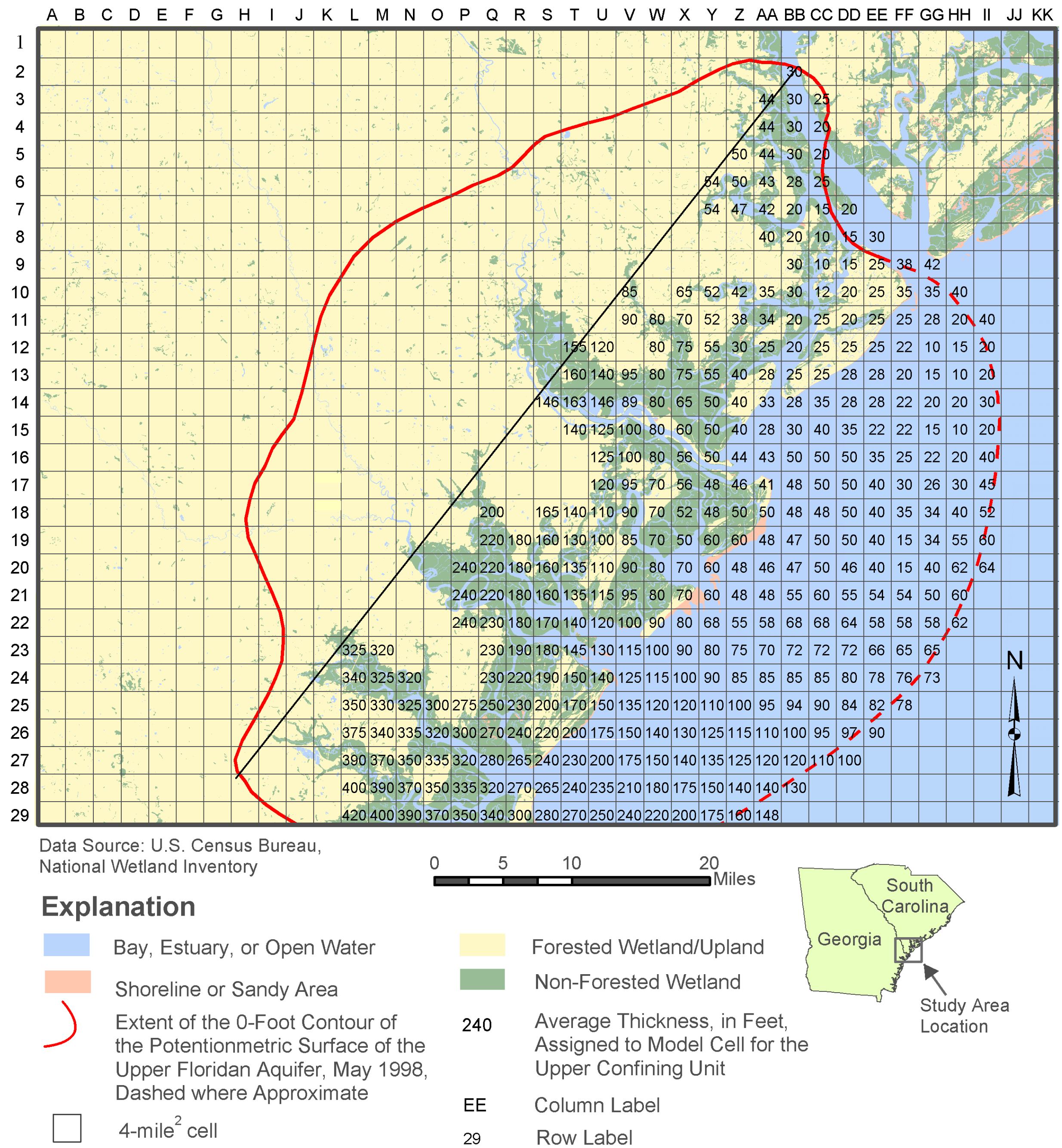
Data Courtesy of the U.S. Army Corps of Engineers

Appendix D. Head Differences and Thicknesses of the Upper Confining Unit



Estimated average head differences through the upper confining unit applied to grid cells in the model.

Appendix D. con't



Estimated average thicknesses of the upper confining unit applied to grid cells in the model.

Appendix D. con't

Cell	Head Difference (feet)	Confining Unit Thickness (feet)	Cell	Head Difference (feet)	Confining Unit Thickness (feet)
AA11	14	34	**FF14**	8	22
AA12	15	25	**FF15**	8	22
AA13	17	28	**FF16**	8	25
AA14	18	33	**FF19**	8	15
AA15	19	28	**FF20**	6	15
BB08	4	2	**GG12**	5	10
BB11	10	20	**GG13**	6	15
BB12	13	20	**GG14**	6	20
BB13	15	25	**GG15**	6	15
BB14	16	28	**GG16**	6	22
BB15	17	30	**HH12**	3	15
CC08	3	10	**HH13**	4	10
CC09	4	10	**HH14**	4	20
CC10	8	12	**HH15**	4	10
CC11	8	25	**HH16**	4	20
CC12	12	25	**X16**	35	56
CC13	13	25	**X17**	35	56
CC14	14	35	**X18**	34	52
DD09	4	15	**X19**	30	50
DD10	5	20	**Y14**	27	50
DD11	8	20	**Y15**	29	50
DD12	10	25	**Y16**	30	50
DD13	12	28	**Y17**	30	48
DD14	12	28	**Y18**	29	48
DD15	13	35	**Z11**	16	38
EE11	7	25	**Z12**	19	30
EE12	8	25	**Z13**	20	40
EE13	10	28	**Z14**	23	40
EE14	10	28	**Z15**	24	40
EE15	11	22	**Z16**	25	44
FF12	7	22	**Z17**	25	46
FF13	8	20	**Z18**	25	50
			Average =	13.86	28

Tabulated head difference and confining unit thickness by grid cell.

Appendix E. One-Dimensional Solute-Transport Equation

$$R_f \frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - V_w \frac{\partial C}{\partial x}$$

Boundary and Initial Conditions:

$$C(x, t = 0) = 0$$
$$C(x = 0, 0 < t \le T) = C_0$$
$$\frac{\partial C}{\partial x}(x = \infty, t) = 0$$
$$C(x = 0, t > T) = 0$$

Solution: The solution to the governing equation and boundary conditions shown above is from Van Genuchten and Alves (1982):

$$C(x,t) = \frac{C_0}{2} A(x,t) \; for \; 0 < 1 \le T$$
$$C(x,t) = \frac{C_0}{2}[A(x,t) - A(x, 1 - T)] \; for \; 1 > T$$

Where:

$$A(x,t) = erfc\left(\frac{x - V_c t}{2\sqrt{Dt}}\right) + \exp\left(\frac{V_c x}{D}\right) erfc\left(\frac{x + V_c t}{2\sqrt{Dt}}\right)$$

$$A(x, t - T) = erfc\left(\frac{x - V_c (t - T)}{2\sqrt{D(t - T)}}\right) + \exp\left(\frac{V_c x}{D}\right) erfc\left(\frac{x + V_c (t - T)}{2\sqrt{D(t - T)}}\right)$$

$$V_c = \frac{V_x}{R_f} \qquad V_x = \frac{K}{n_e}\frac{dh}{dx} \qquad R_f = 1 + \frac{dK_d}{n}$$

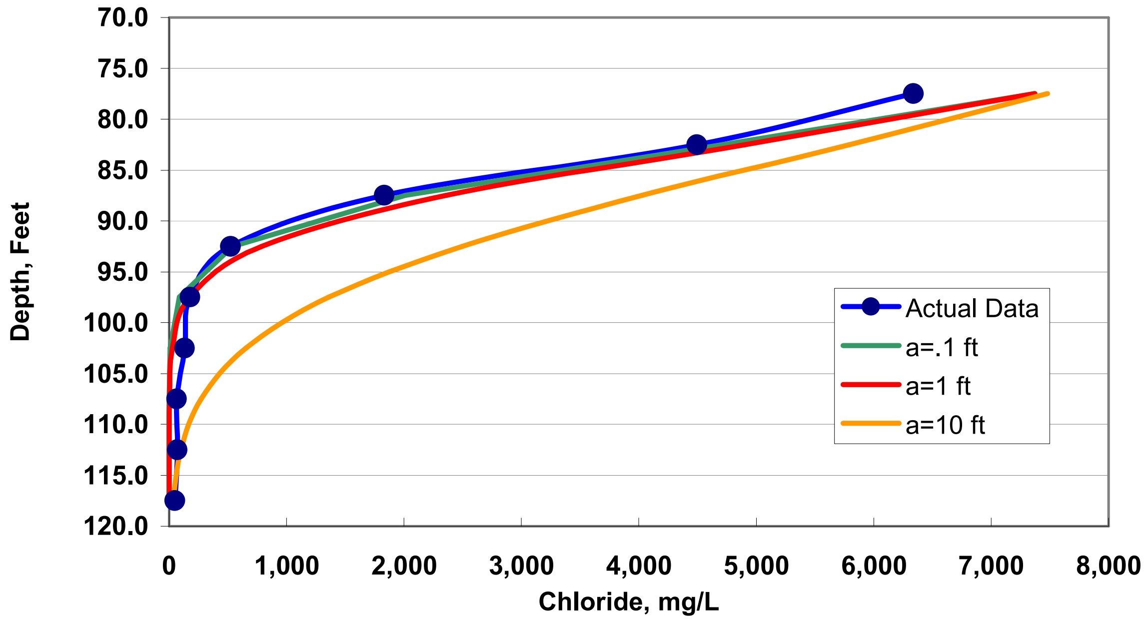
$$K_d = K_{oc} f_{oc} \qquad D = aV_c + \frac{D^*}{n_e}$$

Parameter Definitions [units]:

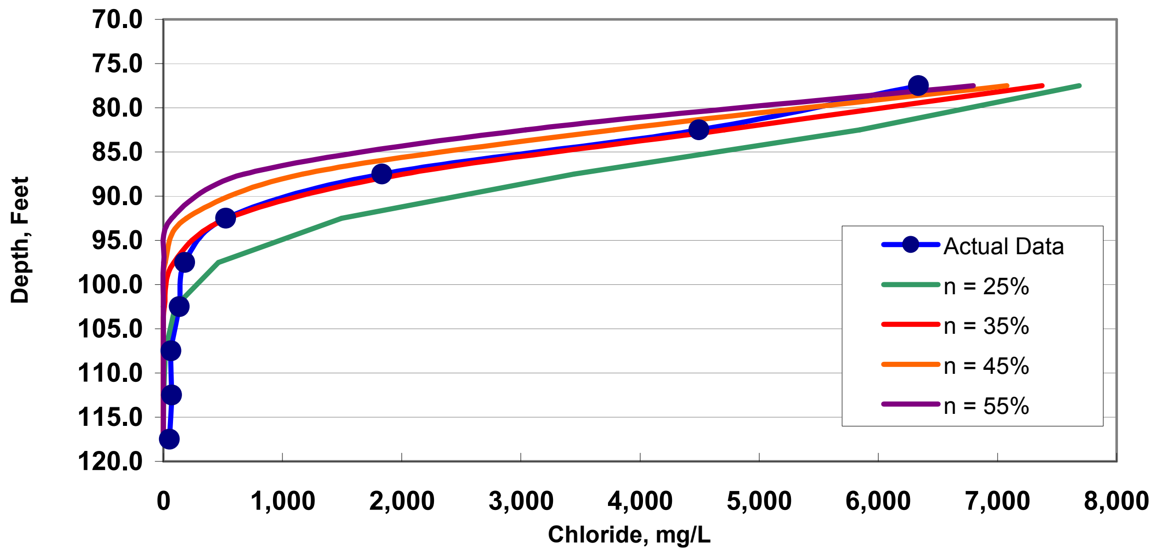
a = Dispersivity [ft]
C = Chemical concentration [mg/L]
C_0 = Injected chemical concentration [mg/L]
d = Dry bulk density of the aquifer [lb/ft^3]
dh/*dl* = Hydraulic (or head) gradient [ft/ft]
D = Dispersion coefficient [ft^2/s]
D* = Molecular diffusion coefficient [ft^2/s]
f_{oc} = Organic carbon fraction in soil [%]
K = Hydraulic conductivity [ft/d]
K_d = Distribution coefficient [ft^3/lb]
K_{oc} = Organic carbon partition coefficient [ft^3/lb]
n = Total porosity (%)
n_e = Effective porosity (%)
P*e* = Peclet number. P*e* = (Vcx) / D
R_f = Retardation factor. R_f = 1 if there is no retardation; i.e., a tracer such as chloride that does not adsorb to the aquifer material
t = Time [yr]. Time at which C_0 is to be calculated
T = Duration of injection [yr] C_0 is injected from *t*=0 to *t*=T
V_c = Mean chemical velocity [ft/yr]
V_w = Pore water velocity [ft/d]. Also known as groundwater velocity.
x = Distance [ft]. Distance at which to compute C.

Appendix F: One-Dimensional Model Sensitivity Analysis

Bull River Site – Measured vs. Simulated Data



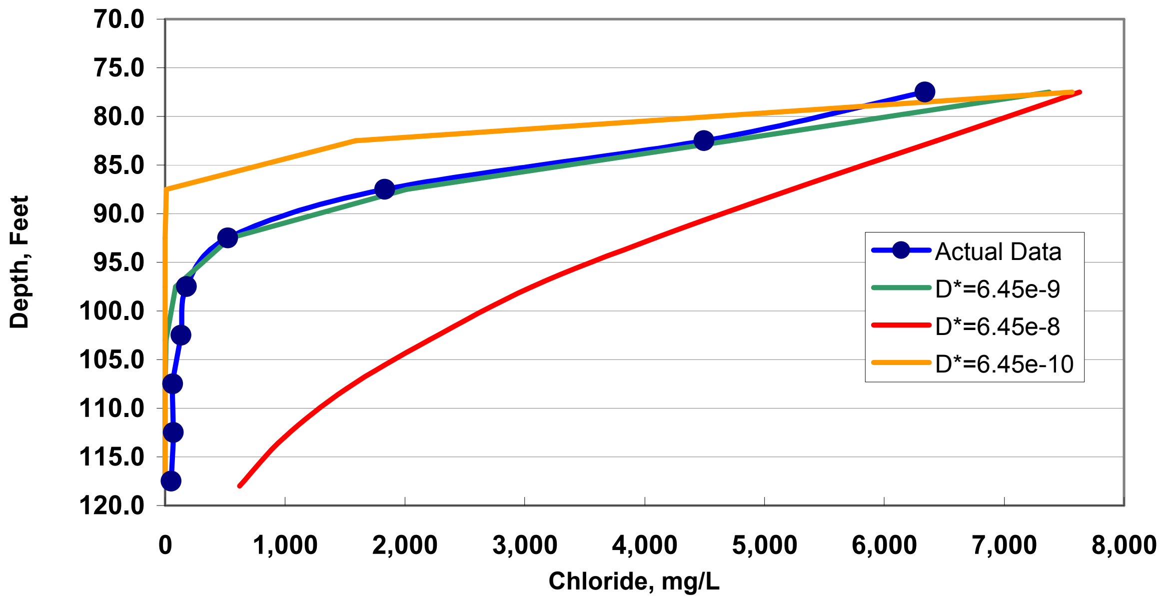
A. Effect of varying dispersivity values (a) on position of simulated chloride profile.



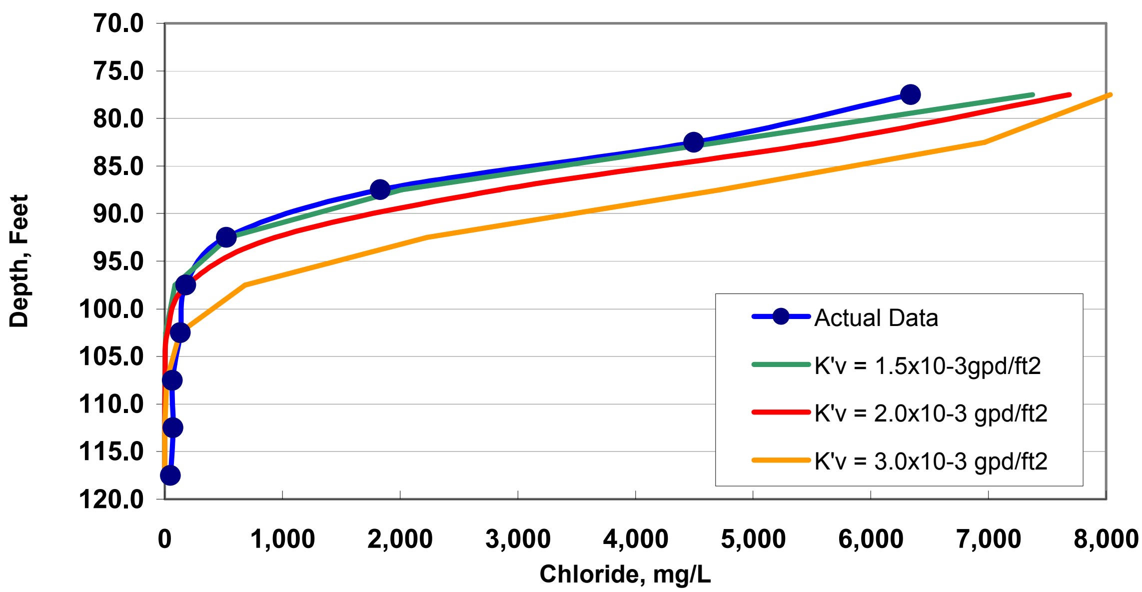
B. Effect of varying effective porosity (n_e).

Appendix F. con't

Bull River Site – Measured vs. Simulated Data

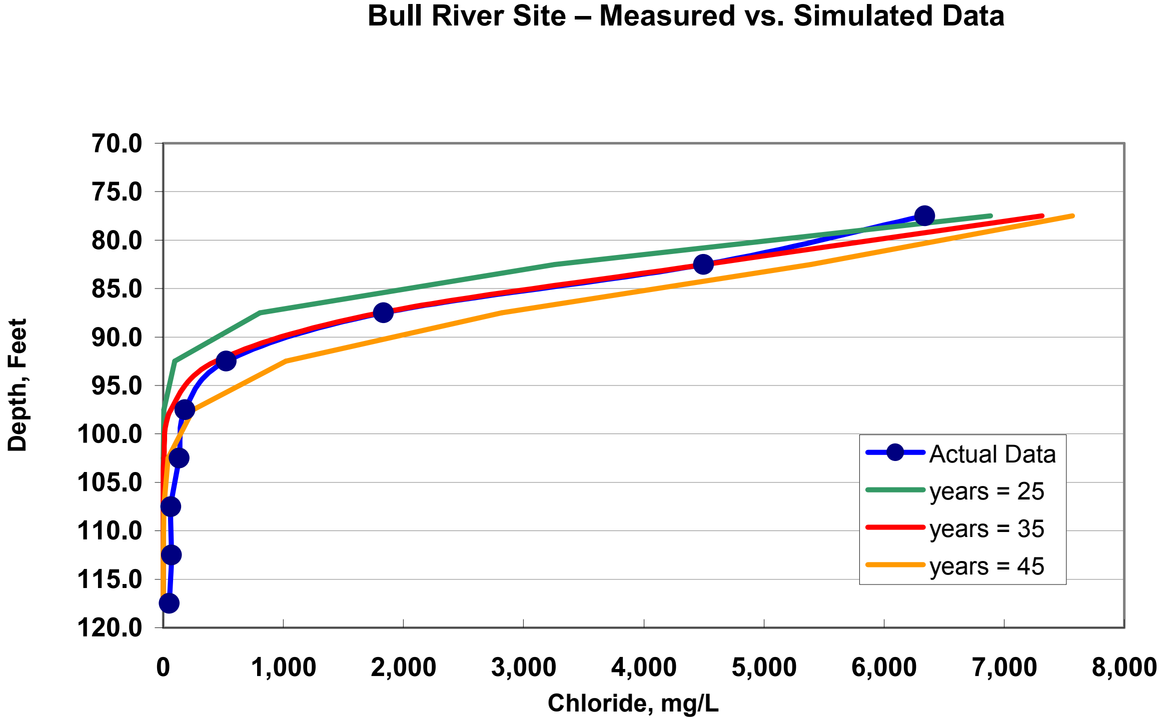


C. Effect of varying diffusion coefficient values (D*).



D. Effect of varying vertical hydraulic conductivity (K'_v).

Appendix F. con't



E. Effect of varying time (in years) since head reversal occurred.